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FLOW AND RETENTION OF WATER IN LAYERED SOILS

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FLOW AND RETENTION OF WATER IN LAYERED SOILS

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~~By~~ D. E. Miller, ~~research soil scientist,~~ *Soil and Water Conservation Research Division, Agricultural Research Service*

Knowledge about the water-retention properties of the soil enables one to estimate the need for and the frequency of irrigation. Satisfactory methods are available (*4*)[1] or being developed (*5*) that can be used to predict the extraction rate of water from the soil by growing plants. If one knows how much water is retained for plant use in the soil after irrigation and how fast it is extracted, the scheduling of irrigations with reasonable accuracy is simple. Such factors as continued deep drainage after irrigation and level of withdrawal before irrigation have to be considered.

The term "field capacity" has been used for many years to refer to the water held by the soil after a thorough wetting and after the downward drainage has become small. It is recognized as an arbitrary range on a time drainage curve and cannot be defined exactly for many soils. Because knowledge of the water-retention properties of soils is essential, considerable effort has been spent in developing laboratory procedures for estimating field capacity. The moisture equivalent and the $\frac{1}{3}$-bar percentage are examples. For coarse-textured soils, the $\frac{1}{10}$-bar percentage has been used frequently. However, such laboratory procedures only estimate field capacity and apply only to uniform soil.

Many irrigated areas are on highly stratified soils, including those with coarse layers in the profile. The water retained by a soil is affected by the characteristics of the entire wetted part of the profile. The restriction of water movement by a coarse layer in a soil was recognized many years ago. In 1917, Alway and McDole (*1*) observed that soil overlying sand or gravel contained about 6 percent more water than did soil not so underlain. Eagleman and Jamison (*2*) found that a silt loam soil underlain by sand drained to a water content of about 40 percent by volume as compared to a $\frac{1}{3}$-bar value of 27 percent by volume. Similarly Robins (*11*) reported that field water-holding capacities of fine sandy loam soils underlain by coarser materials were 50 to 60 percent greater than $\frac{1}{3}$-bar values.

The effect of coarse layers in the profile on soil water-holding characteristics must be understood if such soils under irrigation are to be managed properly. The purpose of this report is to summarize research data showing the effect of coarse layers on water retention and to discuss ways of estimating water-retention properties of layered soils.

GENERAL PROCEDURES

The principles of water retention in layered soils were developed in laboratory studies, with model and field profiles, and by numerical techniques.

Laboratory Studies

In a study (*8*) of water infiltration into stratified soil, columns of soil were packed with and without coarse layers. Infiltration rates were measured as a function of time, and the effect of coarse layers was shown as departures from the infiltration-time curve for the nonlayered soil.

Model and Field Profiles

Model profiles were constructed (*7*) with various arrangements of sand or gravel layers. Soil water contents and suctions were measured periodically after a thorough irrigation, with and without evaporation taking place.

Field tests of water retention were conducted on four naturally occurring profiles of soils in the Ephrata, Timmerman, Rupert, and Scooteney series. All profiles contained coarse layers within the upper 60 to 100 cm. of soil. Water and suction measurements were made over a period of 2 to 3 weeks after a thorough irrigation.

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[1] Italic numbers in parentheses refer to Literature Cited, p. 28.

Unsaturated conductivity and desorption data were obtained for the model and field profile materials. Unsaturated conductivities were measured by a steady state outflow procedure using hanging water columns to obtain total suction and suction gradients. Measurements were made at suctions varying from near zero to the lesser of 200 mb. or the suction corresponding to an unsaturated conductivity of about 0.01 cm. per day.

Desorption data were obtained in pressure outflow units. Soils were packed dry in the units with a hydraulic press to approximate field bulk densities. Desorption measurements were made on the second desorption cycle. Hysteresis effects were not considered.

Numerical Techniques

Hanks and Bowers (*3*) developed a computer program for estimating solutions to the flow equation for layered soils. In this program, hysteresis was not considered. The program requires input data for the soil in question—unsaturated conductivities, diffusivities, desorption curves, and initial conditions.

This program was used to compute water-retention values for the model profiles and to estimate water retention as a function of soil depth and coarseness of underlying layers. To estimate the effect of coarseness of the underlying layer, the procedure of Miller and Miller (*9*) was used.

EFFECT OF LAYERING ON INFILTRATION RATES

Infiltrating water moves into and through the soil at a rate dependent on the nature of the transmitting pores, their water content, and the driving forces existing and developing as flow takes place. According to Darcy's law (*10*), water flow through soil may be considered as $V=Ki$, where V is the velocity of water flow, K is the conductivity of the soil under a given set of conditions, and i represents the driving forces in terms of hydraulic gradient.

As the larger pores empty of water, the resistance to water movement through the soil increases rapidly (K in this equation decreases). Even though micropores may be filled with water at relatively high suctions, the amount of water that passes through them may be small because of the low conductivity. On the other hand, macropores empty of water at relatively low suctions. In emptied pores, liquid flow is restricted to thin films of water along the particle surface. The conductivity of these films is very low and the amount of water that passes through large pores after most of the water has drained out will be small.

If the wetting front encounters a material in which most of the pores are either larger or smaller than those through which it is moving, the infiltration rate will be affected as the hydraulic conductivities and the hydraulic gradients are affected. The magnitude will be determined by the degree of pore size difference between the materials.

When a wetting front contacts a finer pored material than that in which it has been moving, the fine pores begin to fill rapidly because of their great attraction for water. This increases the hydraulic gradient in the wetted soil, and when the wetting front first reaches the finer material, infiltration rates momentarily may be increased slightly as a thin layer is wetted. However, as the wetting front advances into the material, water must be transmitted through the fine pores that have filled—pores with a very low conductivity. Water movement through the pores becomes slow, and the hydraulic gradient within the wetted soil above the fine pored material decreases to such a low value that soon after the wetting front contacts the fine layer, infiltration rates will be reduced.

When a wetting front moving in a soil of relatively fine porosity contacts a predominantly large pored material, the volume of pores capable of holding water at the suctions existing at the wetting front is reduced. Before the wetting front can advance, the water suction at that point must decrease until it is low enough to allow the large pores to fill with water. Restriction of the wetting front advance reduces the hydraulic gradient along the wetting column, and the infiltration rate is decreased. Water continues to enter the system in response to the small gradient, and eventually the water suction at the interface becomes low enough so that a number of large pores can fill.

Such a qualitative effect of fine (clay) and coarse (sand) layers on infiltration rates was given by Gardner.[2] His data are shown in figure 1. The effects of the coarse layers were discussed in more detail by Miller and Gardner (*8*).

The relative size of the pores in the coarse material compared with the pores in the soil above determines the degree to which infiltration is affected, as shown by Miller and Gardner (*8*). Some of their data are given in figure 2. The larger the pore in the sand layers, the greater was the decrease in infiltration rate after the wetting front reached the layer of large pored material.

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[2] GARDNER, W. H. MOISTURE MOVEMENT IN SOILS. Paper presented in symposium: Soil Factors and Absorption. Joint sess. Amer. Soc. Hort. Sci., Amer. Bot. Soc., and West. Soc. Soil Sci., Pacific Div., Amer. Assoc. Advn. Sci., Pullman, Wash., 1954.

When water finally wets and moves through a sand layer, the infiltration rate increases rapidly momentarily (figs. 1 and 2). As the water passes through an initially dry sand layer, it characteristically wets the sand in only a few places, and elsewhere the sand remains dry. Liquid movement through the sand is restricted to the water-filled channels. As water moves into the soil below the

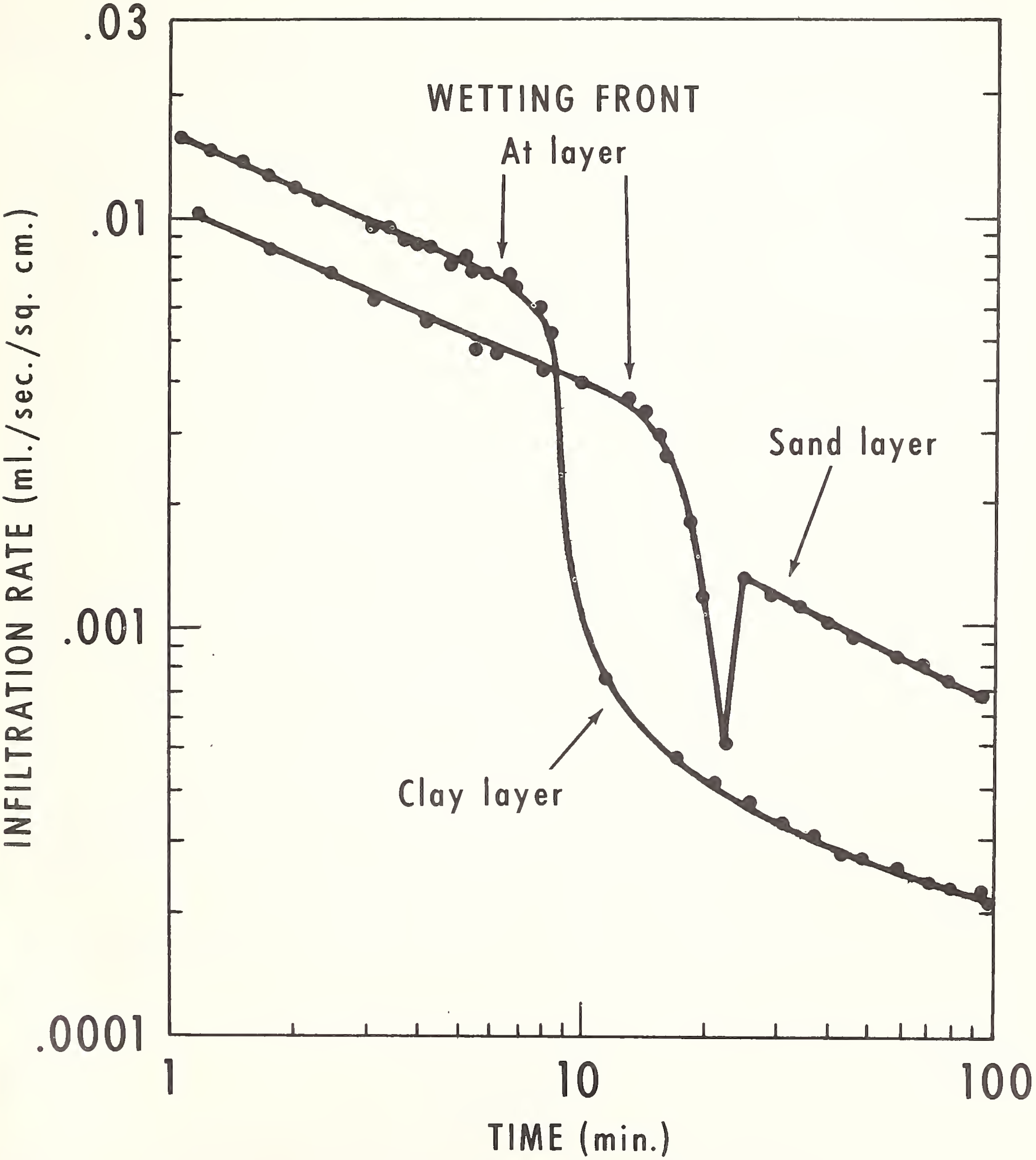

FIGURE 1.—Effect of sand and clay layers on infiltration rate into Palouse silt loam as function of time. [From Gardner (see footnote 2, p. 2).]

sand layer, the high attraction of the soil for water causes an immediate increase in hydraulic gradient and in infiltration rate consistent with the conducting capacity of the channels in the sand. However, as the soil below the sand is wetted to greater depths, the total flow path and thus the total resistance to flow increases, and the rate of water movement decreases. At the same time, as water suction decreases at the soil-layer interface, more and more of the sand becomes wet so that its capacity to conduct water increases. Thus after a short time the sand layer no longer inhibits infiltration (fig. 2). For soil overlying a deep deposit of coarse material, the infiltration rate should eventually approach the saturated conductivity of the soil and the hydraulic gradient should approach unity.

The effect of the coarse layer on infiltration will be determined by the depth of soil above the layer. The rate of increase in water content at a point within the wetted zone decreases with distance from the source of free water. Thus the time during which infiltration is inhibited by a layer of large pored material should increase as the distance from the layer to the water source increases. As this distance increases, the amount of soil accumulating water also increases, so that the infiltration rate should decrease more slowly. This was shown by Miller and Gardner (*8*). Some of their data are given in table 1.

Table 1.—*Effect of distance from water source on time between wetting front reaching and crossing soil-sand interface and on decrease of infiltration rate due to interface (downward wetting)* [1]

Distance from water source to coarse layer (cm.)	Time required for water to cross soil-sand interface	Average rate of decrease of infiltration rate after wetting front reached sand
	Sec.	*Cm. per sec.*$^2\times 10^5$
4	105	3.60
8	180	.55
12	390	.23

[1] Data from Miller and Gardner (*8*).

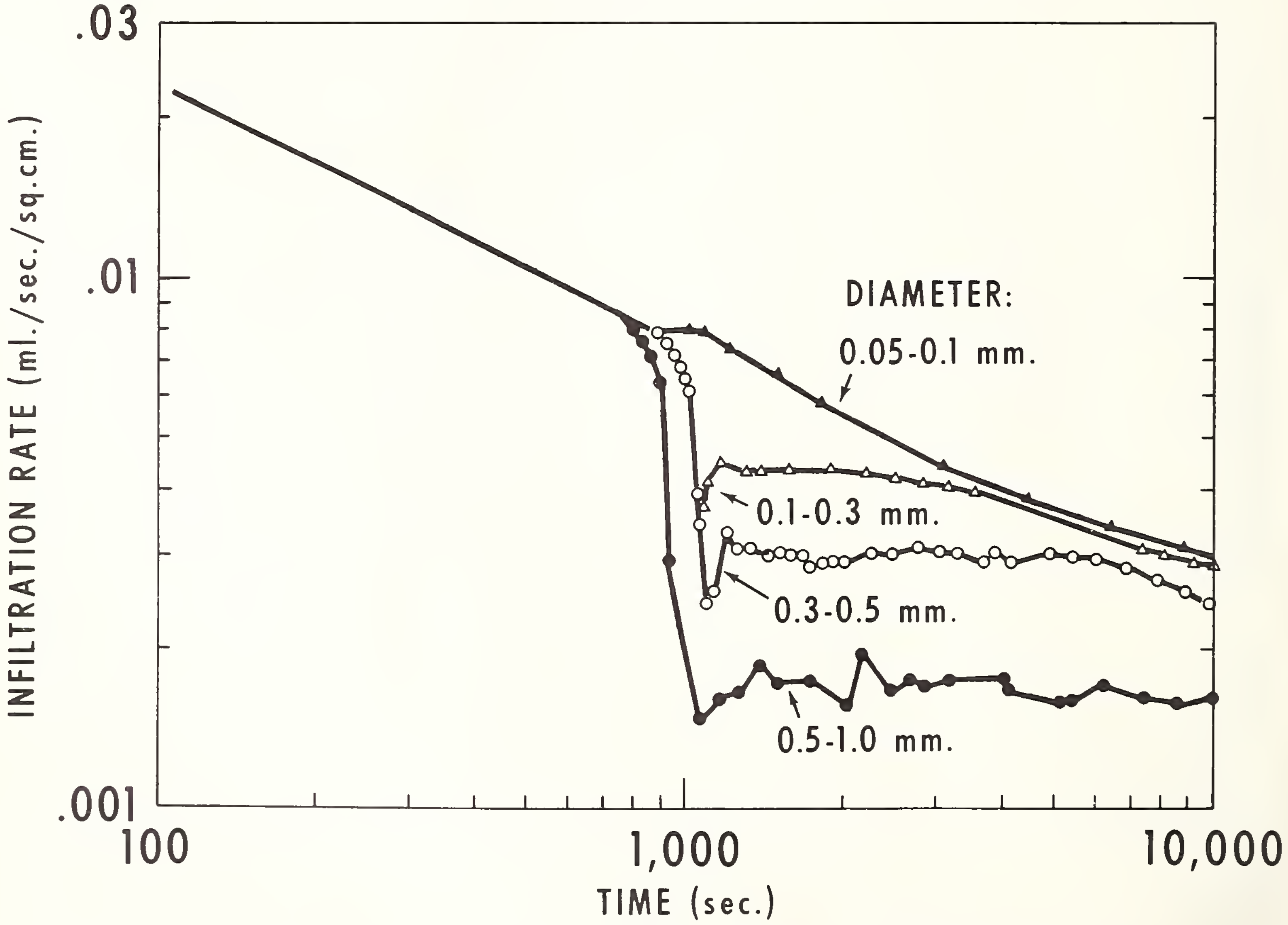

Figure 2.—Effect of subsurface layers of sand on infiltration into standard soil as function of time for downward wetting. Layers were 0.5 cm. thick at 8-cm. depth. [Data from Miller and Gardner (*8*).]

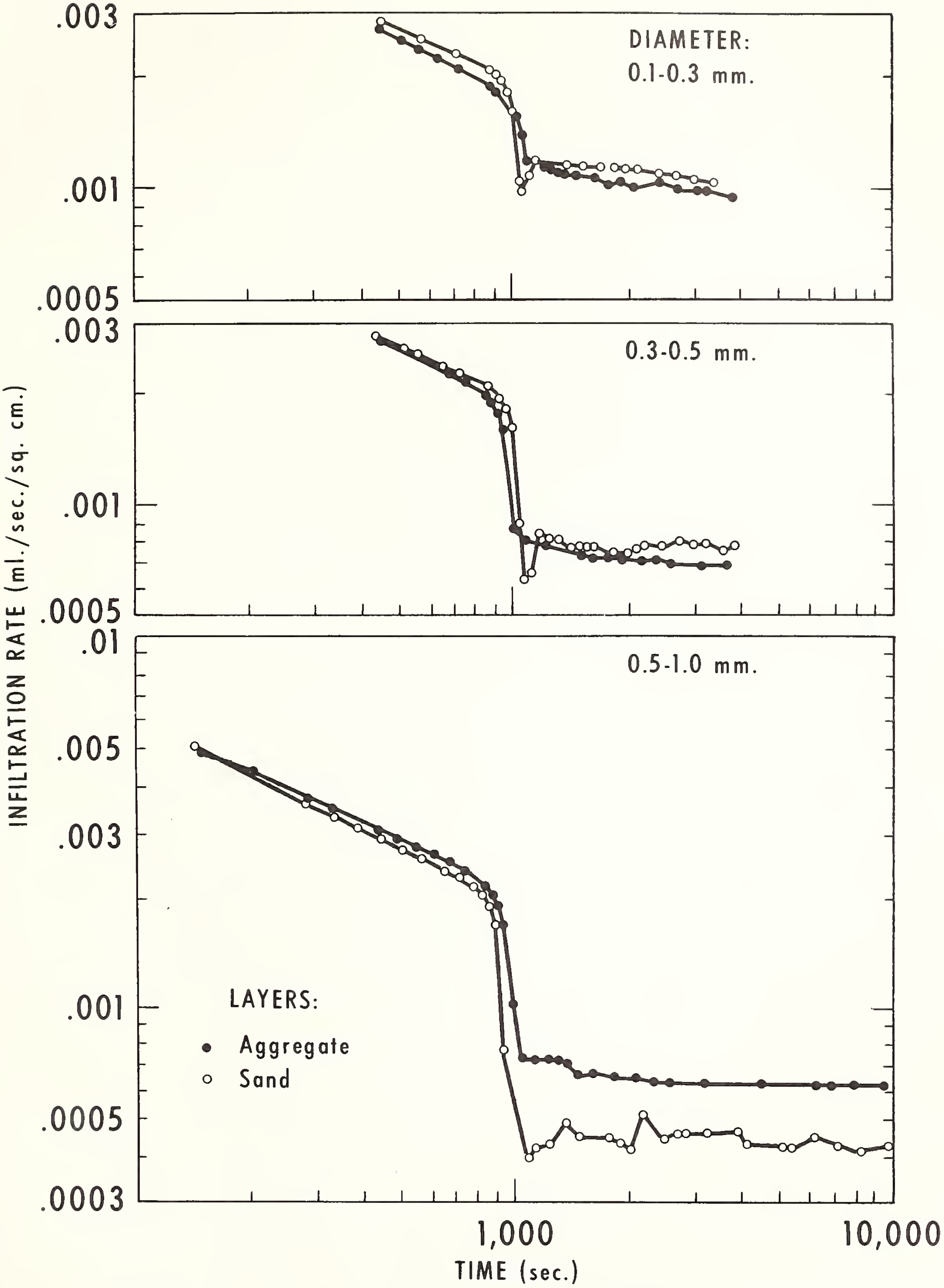

FIGURE 3.—Comparison of effects of layers of similar sized aggregate and sand separates on downward infiltration into standard soil as function of time. Layers were 0.5 cm. thick at 8-cm. depth. [From Miller and Gardner (8).]

Any change in pore size will affect the advance of the wetting front and thus infiltration. If a layer of predominantly coarse aggregates is encountered by the wetting front, the effect will be similar to that caused by a sand layer except that small amounts of water can move through the aggregates.

A comparison between sand and aggregate layers of the same size range is given in figure 3. Infiltration was inhibited more by a sand layer than by an aggregate layer of the same size range. In addition, the presence of an aggregate layer did not result in an increased infiltration rate immediately after the wetting front passed through the layer, as was characteristic when sand layers were present. Both of these differences are explained on the basis of small pores within the aggregates, which are not found in the sand particles.

Some of the problems observed in field irrigation, when it has been difficult to get water to move laterally out of a furrow into the ridge, probably are due to an interference in flow between the compact soil in the furrow and the loose soil between furrows.

WATER RETENTION BY MODEL PROFILES

Procedures

In the study of water retention with model profiles, data were collected over a 2-month period after irrigation, with evaporation prevented. The profiles were irrigated again and evaporation was allowed. They were then cropped for several years and the water availability was related to the profile characteristics. Laboratory data were obtained to formulate relationships by which water-holding characteristics of soils with coarse layers in the profile could be estimated. These data were used in a computer program to estimate water-retention properties of various layered profiles.

Six profiles were constructed with various combinations of soil, sand, and pea gravel. The profiles were constructed in pits, 2.4 m. (8 ft.) by 3 m. (10 ft.) in area and 1.5 m. (5 ft.) deep, which were lined with polyethylene film to prevent lateral movement of water. The soil from the pits was thoroughly mixed and replaced with the sand and gravel layers. Thus all the soil was similar, and the profiles differed only in layering with coarse materials. The soil was of a sandy loam texture containing 54 percent sand, 39 percent silt, and 7 percent clay (by hydrometer). The sand and gravel were river washed and sieved materials obtained from a local concrete mixing company. Approximately 70 percent of the sand was between 0.25 and 2 mm. in diameter and approximately 25 percent was larger than 2 mm. The gravel particles were between 6 and 13 mm. in diameter. Details of the construction of the profiles are given by Miller and Bunger (7).

Tensiometers were installed at various depths in the profiles and a neutron meter access tube was placed in the center of each plot. The plots were irrigated and allowed to stand over winter. The first test irrigation was made in early June of 1961. Sufficient water was added to bring the soil above a layer to 35 percent by volume. For the uniform soil, sufficient water was added to bring the upper 61 cm. (2 ft.) of soil to 35 percent by volume. The water in excess of the water-holding capacity moved deeper into the soil. After irrigation, evaporation was prevented with polyethylene film and straw. Soil water and suction observations were made periodically over a 2-month period, after which the profiles were again irrigated as before. The surface was left open to evaporation and soil water contents and suctions were observed for 1 month. The following year (1962) the plots were cropped to wheat and in 1963 and 1964 to alfalfa.

After the final observations in 1961 on plots irrigated and left open to evaporation, the profile area was seeded to winter wheat, including the plots and the areas between plus a strip 1.2 m. (4 ft.) wide around the plots. Fertilizer was applied prior to seeding at 200 pounds nitrogen, 43.7 pounds phosphorus, and 45 pounds potassium per acre.

Water use measurements were made in the spring of 1962, starting in April. On April 10, water measurements were made on all plots. Sufficient water was added to each plot to bring it to a water content equal to that observed 4 days after irrigation in the retention study of the previous year, an arbitrary estimate of field capacity. The plots were irrigated on April 11, and water and suction measurements were made at frequent intervals.

The basis for reirrigation was arbitrarily taken as about 15.5 percent water by volume at a depth of 38 cm. This corresponds roughly to a suction of about one-half bar on a laboratory desorption curve. It is not possible to select a basis for irrigation that would be common to all the profiles because of the differences in soil depths and water-retention properties. For example, irrigation at a water content of 15.5 percent by volume at 38 cm. deep was equivalent to irrigation when 60 percent of the available water at this depth was depleted from the uniform soil and when more than 70 percent of the available water at this depth had been removed in the soils underlain by sand or gravel. In addition, for profiles underlain at 61 cm. by coarse layers, the root zone was restricted to this depth of soil. In the uniform soil and the soils underlain at 122 cm., considerable water would be available to the plant at depths below 61 cm. when the water above this depth was nearing depletion.

In 1963 the plots were cropped to alfalfa, which had been planted late in the summer of 1962. After the alfalfa was about 20 to 25 cm. high (Apr. 24), the plots were all irrigated as in the previous year. Water contents and suctions were measured until the first harvest, with no further irrigation. After the first harvest, the alfalfa was irrigated lightly. When the regrowth was 20 to 25 cm. high, the plots were irrigated and water contents and suctions were measured again until harvest, with no further irrigation.

Results and Discussion

Evaporation Prevented

Three of the profiles consisted of 61 cm. of soil underlain by about 8, 30, or 91 cm. (3, 12, or 36 in.) of sand. The water-retention properties of the soil above the sand were almost identical for these three profiles, indicating that a small textural break is sufficient to affect the water-retention properties of a soil. Because of the similarity of these three profiles, only the profile of 61 cm. of soil underlain by 30 cm. of sand will be compared with the other profiles.

The amount of water retained in the soil over a coarse layer was much greater than in a similar depth of uniform soil at any given time after irrigation. This effect is illustrated by the data in figure 4. Here the water contents at a 30-cm. depth, as a function of time after irrigation, are given for the uniform soil, sand at a depth of 61 and 122 cm., and gravel at a depth of 122 cm. The suctions at the same depth are also shown. These data illustrate several of the principles of water retention in layered soils.

The suctions in a soil underlain by coarse materials remain much lower than in a uniform soil. This effect is related to the unsaturated conductivities of the coarse-layer material. At relatively low suctions the large pores within the sand empty of water and are not able to conduct appreciable water, even at high hydraulic gradients. Inasmuch as most of the pores in the coarse material are large, the unsaturated conductivity becomes very small at low suctions. In order for the water in the soil to decrease, it must flow through the coarse layer. The hydraulic conductivity of the coarse layer is so low at the suctions involved that there is an effective barrier to further drainage. The soil water suction at the soil-layer interface will be in that range at which the coarse material loses ability to conduct appreciable water.

At the high water contents in the soils over coarse layers, suction equilibrium within the soil is attained rapidly. As shown in figure 5, the hydraulic gradients in a layered soil approached zero above the layer soon after irrigation (the suction increased by about 1 mb. for each centimeter increase in height above the interface). This is also illustrated in figure 4 by the suctions at 30-cm. depth in soil underlain at 61 or 122 cm. by sand. The deeper the soil over the layer, the greater is the suction at equilibrium near the surface and the difference is determined by the elevation above the interface.

Inasmuch as gravel has larger pores than sand, soil above gravel drains to lower suctions than soil above sand, as illustrated in figure 4 by the suctions in soil underlain by sand or gravel at 122-cm. depth.

Since the water contents are determined by the soil water suctions, one should expect water content differences as indicated in figure 4. The uniform soil with no barrier to flow continues to drain for many days after irrigation. The layered soils essentially stop draining within a few days. Because the soil drains to a lower suction over gravel than over sand, the water contents in soil over gravel will be higher than over sand (fig. 4). Also because the suction increases with height above an interface, the water contents will decrease with elevation above an interface. Thus in figure 4 the water content at a depth of 30 cm. is greater in soil underlain by sand at 61 cm. (31 cm. above the interface) than in soil underlain at 122 cm. (92 cm. above the interface).

Available water is usually considered to be the water held by a soil at some arbitrary time after irrigation in excess of the permanent wilting percentage (15-bar percentage). On this basis, consider the available water held in the soil 1 week after irrigation, as indicated in figure 6. The soil over sand retains about 50 percent more available water than does an equal depth of uniform soil, whereas soil over gravel retains about 60 percent more. For most crops, it is injurious to deplete the soil water to the wilting range. If one takes the usable water before irrigation as the upper 50 percent of available water in the uniform soil, the same depth of layered soil will hold about twice the usable water of the uniform soil. Thus irrigation frequency in a soil underlain by coarse layers will be only about one-half what one would expect in that depth of soil if one bases the estimates on the water-retention properties of uniform soil. Similar conclusions may be obtained for this soil by comparing the amount of water retained in the various profiles at suctions lower than some value, such as about 1 bar.

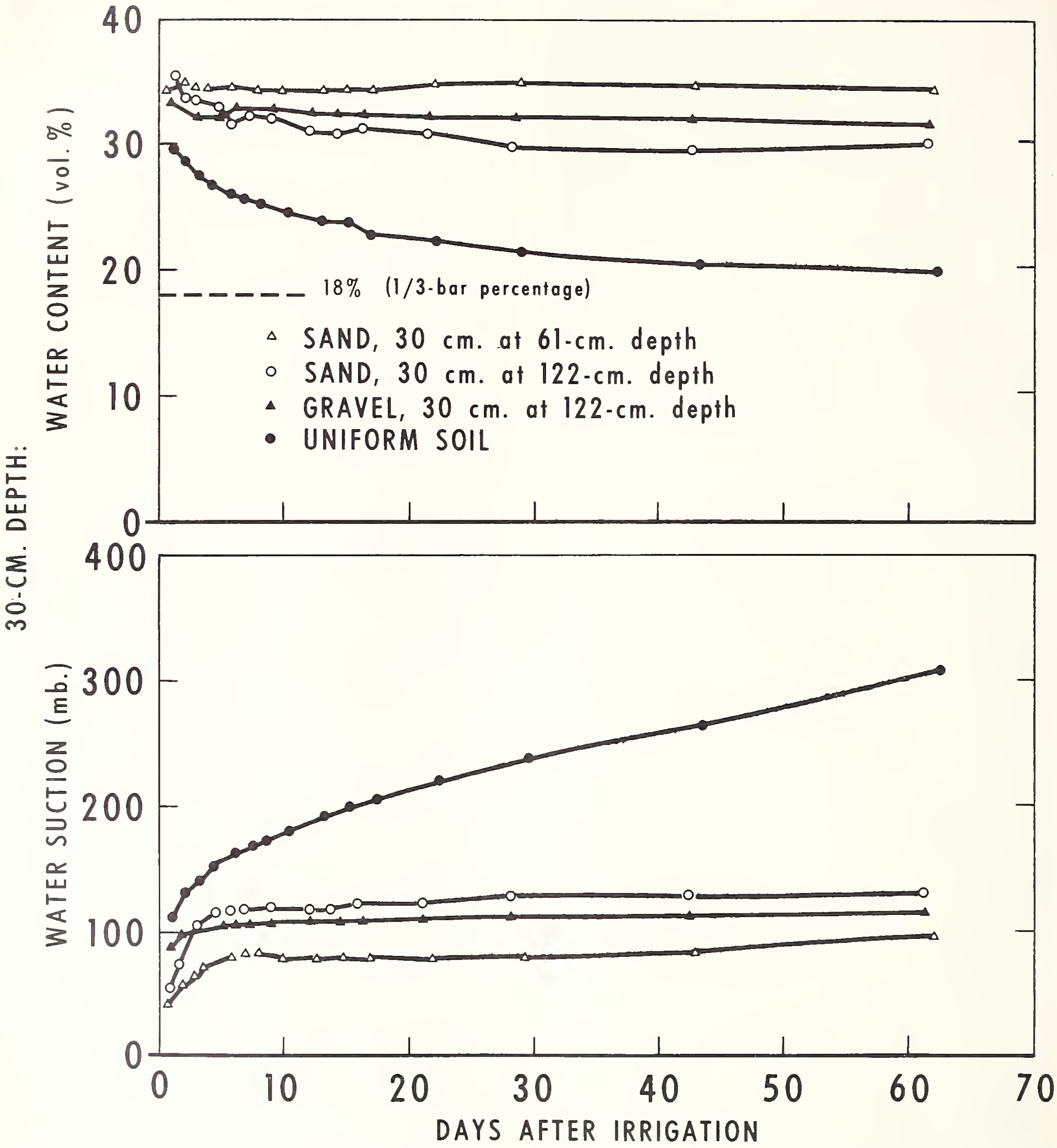

Figure 4.—Water content and suction at 30-cm. depth in uniform soil and soil underlain by sand at 61- and 122-cm. depths and by gravel at 122-cm. depth as affected by time after irrigation. Surface evaporation prevented.

Evaporation Not Prevented

As would be expected, the soil dried out faster and the water suction rose more rapidly and to greater values when evaporation was allowed than when it was prevented.

The water content in the upper 61 cm. of soil decreased more rapidly and to lower values,

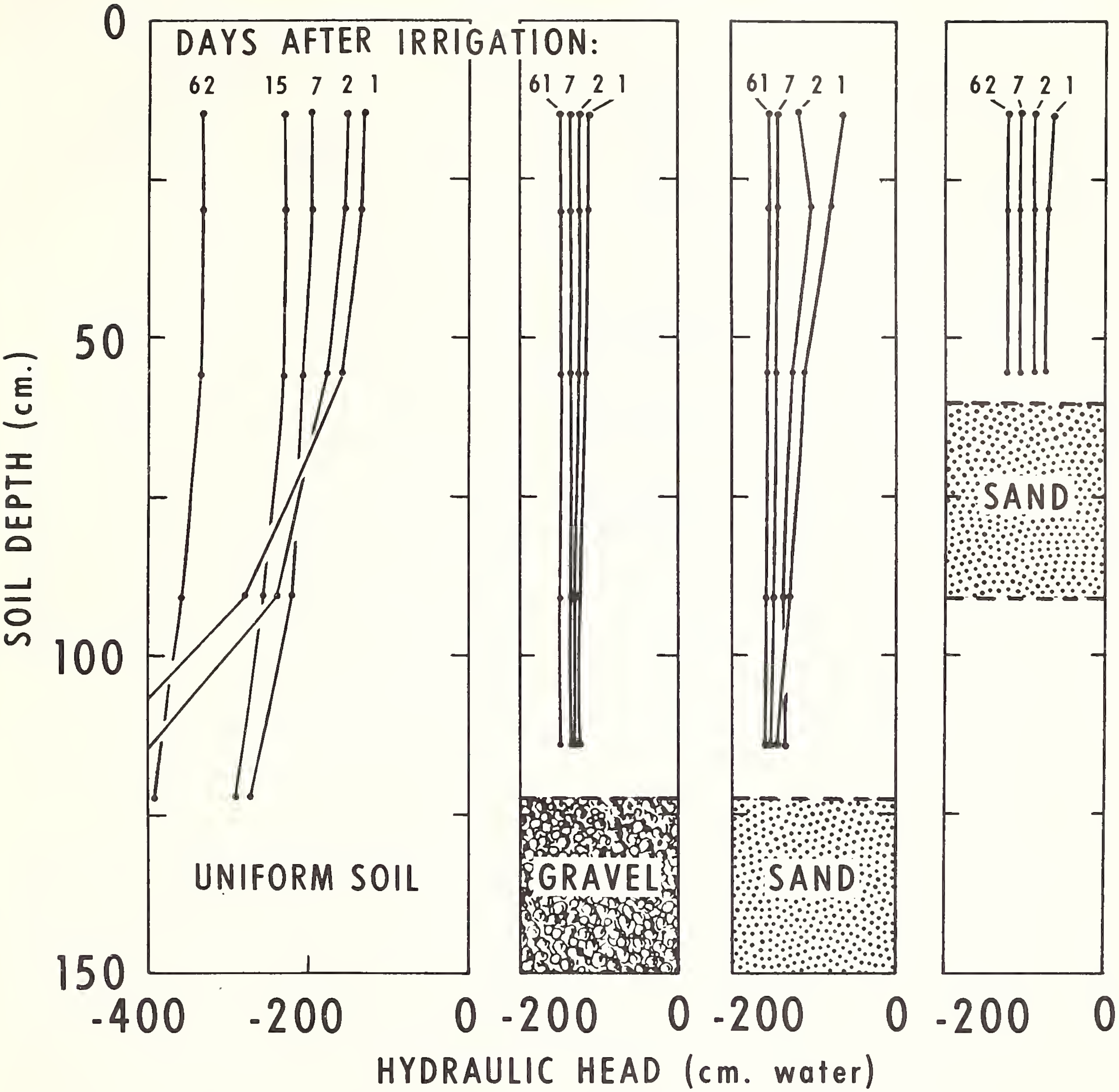

FIGURE 5.—Hydraulic head (soil surface as reference) as affected by time after irrigation and by coarse layers in profile. Evaporation prevented.

whereas the suction increased more rapidly and to higher values in the uniform soil than in the soil underlain by sand (fig. 7). This effect could be important in seedling establishment. Because of increased water storage and movement of this water to the surface, the surface of layered soil is kept moist for germination longer than that of uniform soil. The water lost from the upper part of the uniform soil by deep drainage reduces the total amount available to replace that lost by evaporation. Also, the unsaturated conductivity near the surface is reduced because of the lower water content in uniform soil.

Hydraulic heads as affected by time after irrigation and soil depth are shown in figure 8 for four of the profiles during the time that evaporation was allowed. There are several noteworthy features to these curves related to the effect of the coarse layer on maintaining high water levels just above the layer.

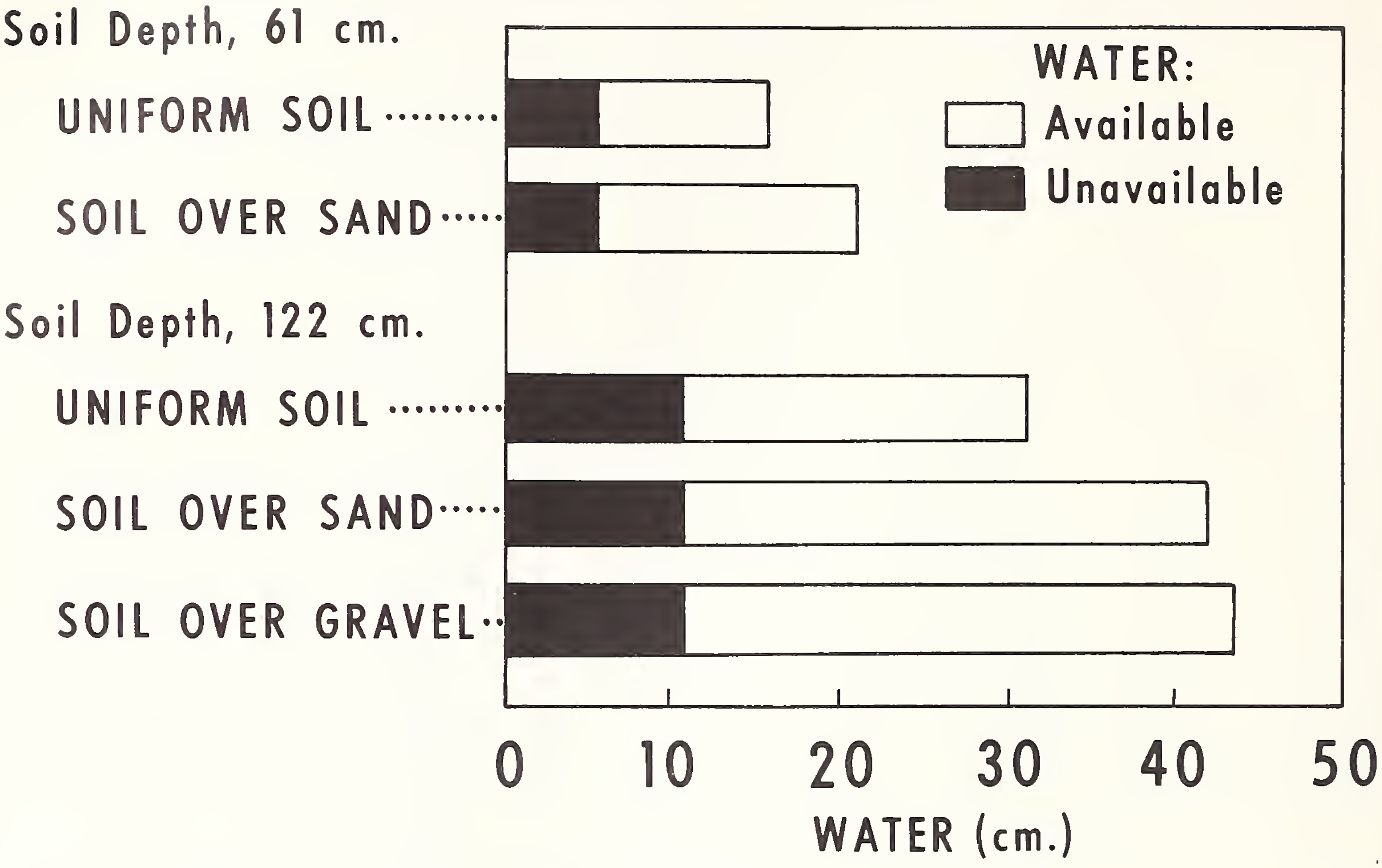

FIGURE 6.—Available water retained by soil 1 week after irrigation as affected by coarse layers in profile. Evaporation prevented.

The hydraulic heads decrease (suctions increase) much more rapidly in the uniform soil than in the layered soils. This decrease in head is due to both deep drainage, predominating shortly after irrigation, and to evaporation losses. In the layered soils, since drainage is small, the decrease in hydraulic head is associated largely with evaporation.

The rate of decrease of hydraulic head in the upper 60 cm. of soil in the deep layered soils (122 cm. of soil over sand or gravel) is less than in the shallower layered soil (61 cm. of soil over sand). This is due to the greater amount of water stored at low suctions in the deep soils and thus readily available to move upward to replace that lost by evaporation.

The downward hydraulic gradients in the layered soils approach zero by the second day after irrigation. In the uniform soil, downward gradients of about 3 cm. of water per centimeter depth were observed in the lower parts of the profile for the entire 29-day observation period.

A sand layer 8 cm. thick was sufficient to prevent upward movement of water from the soil as the soil above the layer dried out (fig. 9). As shown in this figure, the water content above the sand layer (38-cm. depth) decreased with time after irrigation, whereas in the soil below the sand (91-cm. depth) it remained constant. In this profile the soil below the sand layer was underlain by a second sand layer, also 8 cm. thick, at a depth of 61 cm. below the first. This soil was prevented from losing water either upward or downward, except by vapor transfer because of the low unsaturated conductivity of the sand at the suctions involved.

Model Profiles Cropped

Water contents at 30-cm. depth for uniform soil and soil underlain at 61 and 122 cm. by sand are shown in figure 10 for model profiles cropped to winter wheat. Shortly after irrigation the water content in the uniform soil fell much below that of the layered soils as water drained deeper into the profile. It was not until near the time of reirrigation that the water contents of the uniform soil and the soil over sand became similar. Because of the increased water storage in the 122-cm. soil over sand, the interval between irrigations was

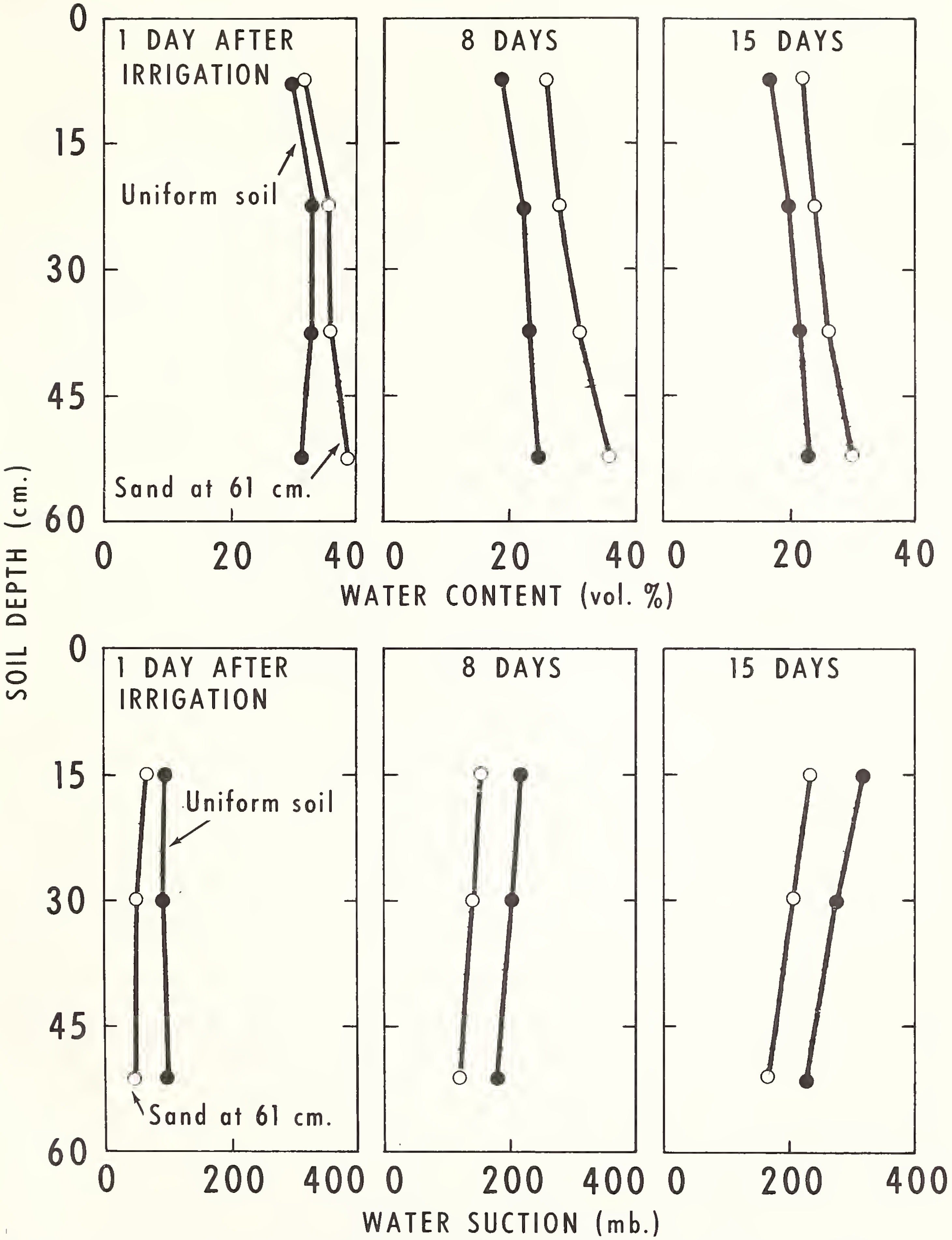

FIGURE 7.—Water content and suction in uniform soil and soil underlain by sand at 61 cm. at various times after irrigation. Evaporation not prevented.

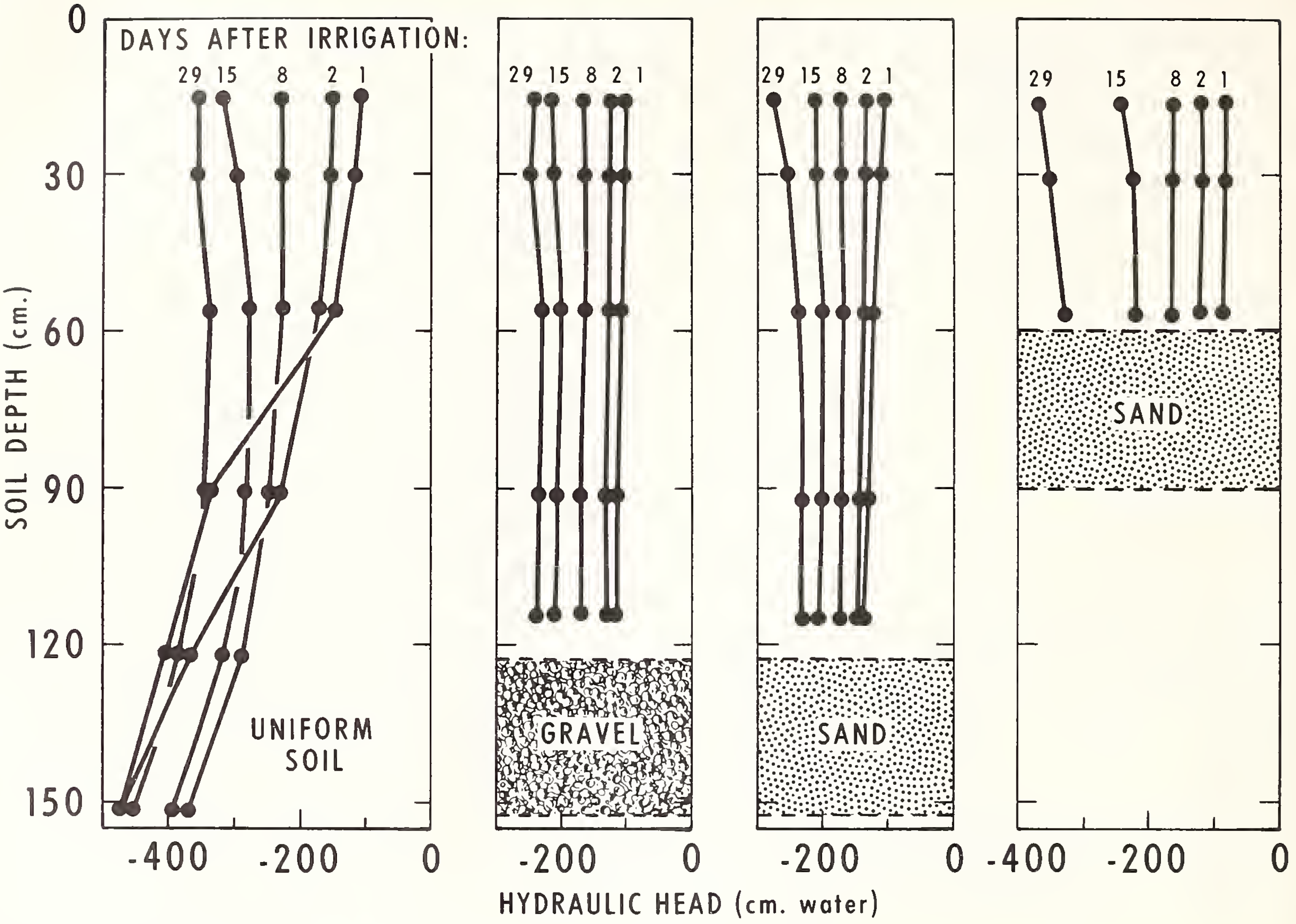

Figure 8.—Hydraulic head (soil surface as reference) as affected by time after irrigation and by coarse layers in profile. Evaporation not prevented.

about twice that of the uniform soil or the 61-cm. soil over sand.

These data substantiate those in figure 6, which show that the available water held by a layered soil is as great as that held by a greater depth of uniform soil. In addition, the water from the layered soils is extracted under much lower suctions than that removed from the uniform soil.

Water contents at 30-cm. depth for uniform soil and soil underlain at 61 and 122 cm. by sand are shown in figure 11 for model profiles cropped to alfalfa. For about the first 3 weeks after irrigation, water contents were higher in all layered soils than in the uniform soil. However, about this time the water in the 61-cm.-deep soil dropped below that of the uniform soil. The readily available water had been depleted from this soil. In the uniform soil the plants could extract water from deeper in the profile and were not forced to dry out the upper 61 cm. to as great an extent. The water content of the profiles underlain at 122 cm. by coarse layers remained well above that of the uniform soil throughout the growth period. At each harvest, the alfalfa on the uniform soil and on the 61-cm. soil over sand showed severe signs of water stress, but such symptoms were not observed on the profile with 122-cm. soil over sand.

Again these data support those previously cited showing that the amount of readily available water in a given depth of layered soil is much greater than that in a comparable depth of uniform soil.

Estimating Water-Retention Properties

Because of the effect of coarse layers on drainage of water from the soil, the usual laboratory procedures for estimating water-retention characteristics of soils, such as $\frac{1}{3}$- and $\frac{1}{10}$-bar percent-

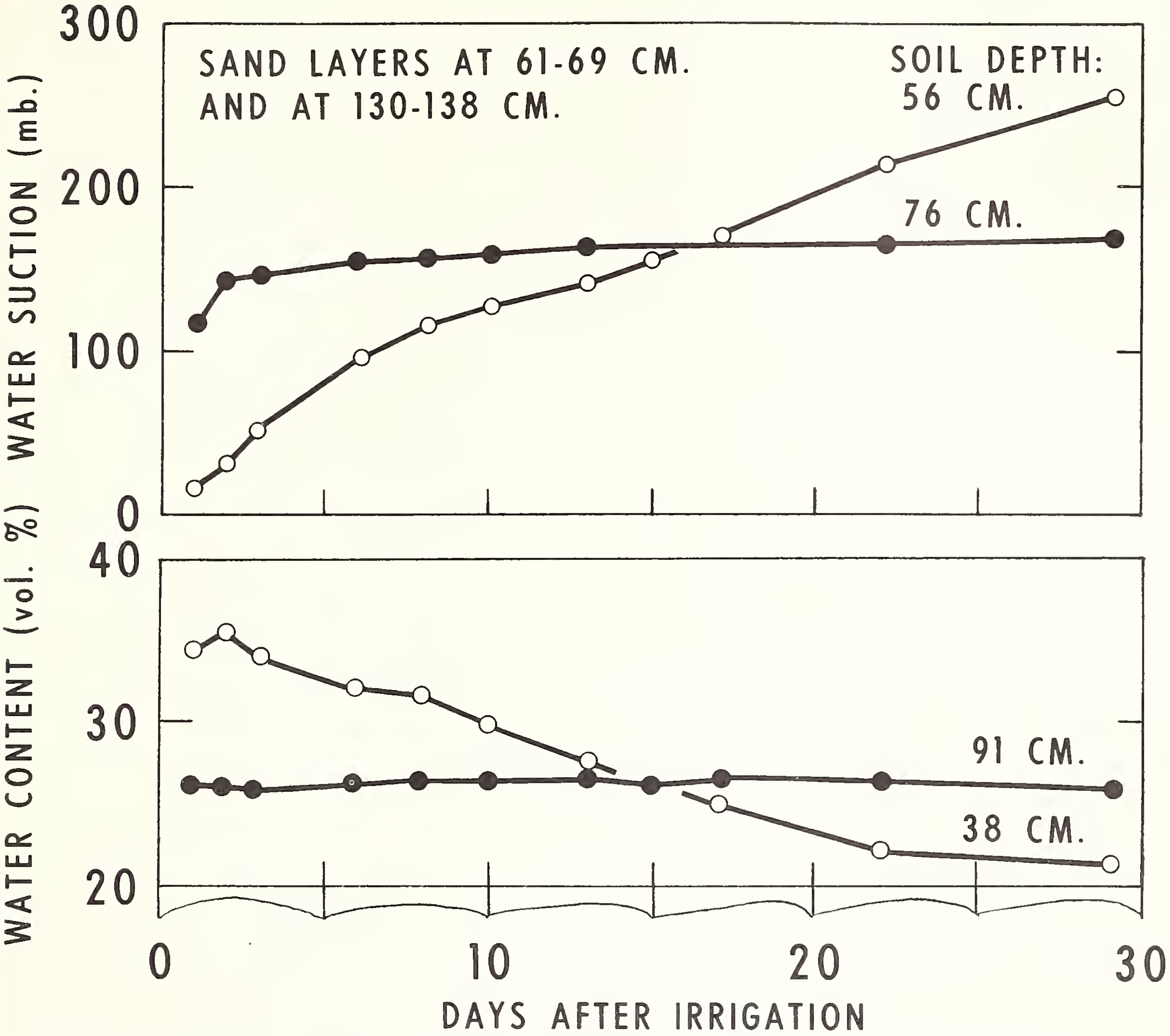

Figure 9.—Water content and suction above and below 8-cm. sand layer as affected by time after irrigation. Evaporation not prevented.

ages, are not applicable to layered profiles. In a layered profile, the unsaturated conductivity of the coarse layer and the desorption properties of the soil over the layer combine to dominate the water-holding characteristics of the soil. Thus a laboratory estimate of the water-holding capacity of a layered soil should include measurements of these characteristics.

Unsaturated conductivities of the soil and coarse-layer materials from the model profiles were measured and a desorption curve was made for the soil. These data are given in figures 12 and 13.

If one assumes a negligible rate of drainage from a profile, it is possible to estimate from the unsaturated conductivity curve the suction within the coarse layer at which this rate of drainage will occur, assuming a hydraulic gradient of 1 within the coarse material. Inasmuch as the soil above the coarse layer cannot drain to a higher suction than that in the underlying material, the suction at the soil-layer interface may be estimated. Then, because of the rapidity of suction equilibrium at the low suctions involved (fig. 5), the suction in the soil may be assumed to increase by about 1 mb. per centimeter of increase in elevation above the

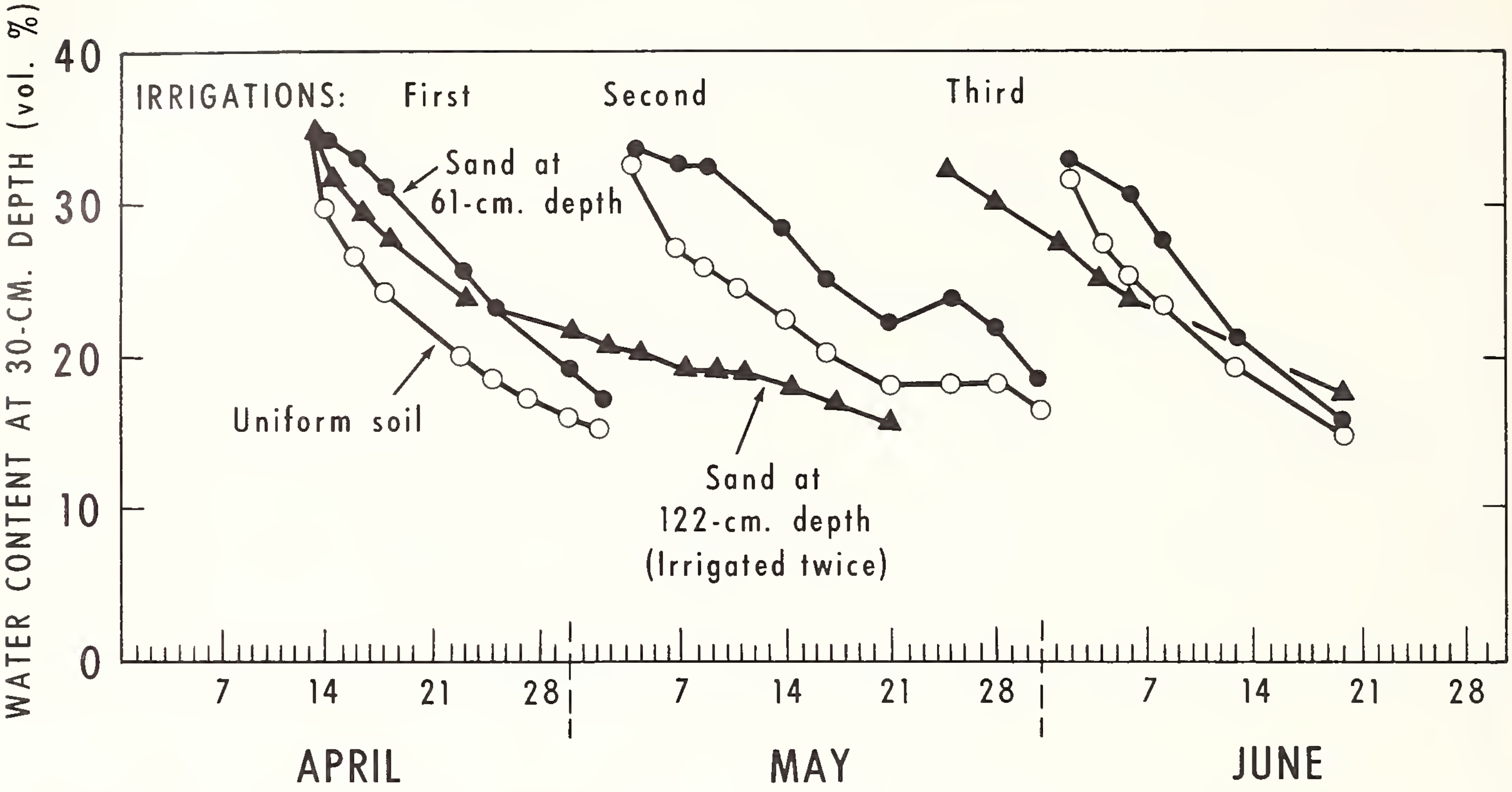

FIGURE 10.—Water content at 30-cm. depth in uniform and layered soil as related to time after irrigation for winter wheat. Sand layers are 30 cm. thick.

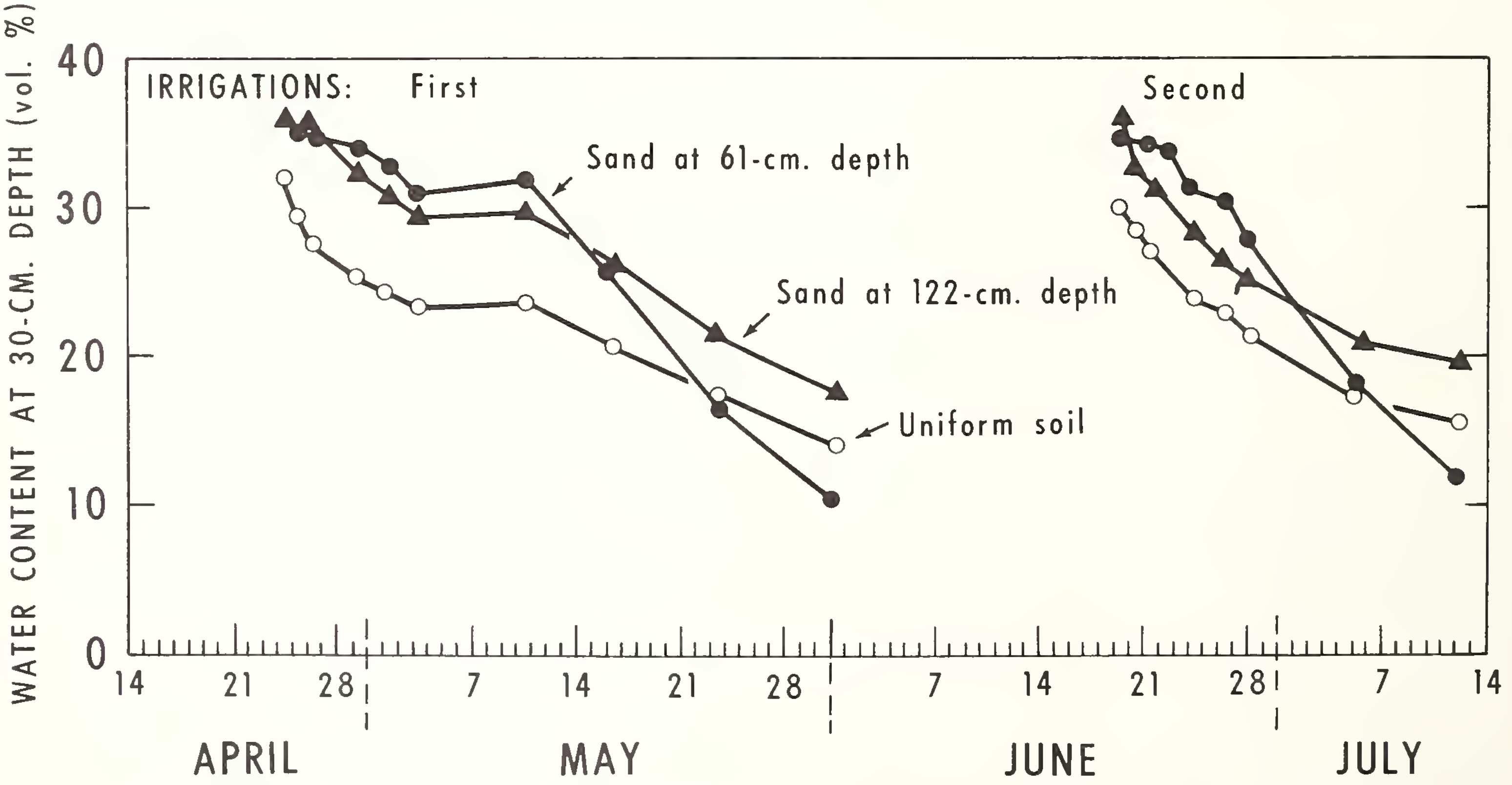

FIGURE 11.—Water content at 30-cm. depth in uniform and layered soil as related to time after irrigation for alfalfa. Sand layers are 30 cm. thick.

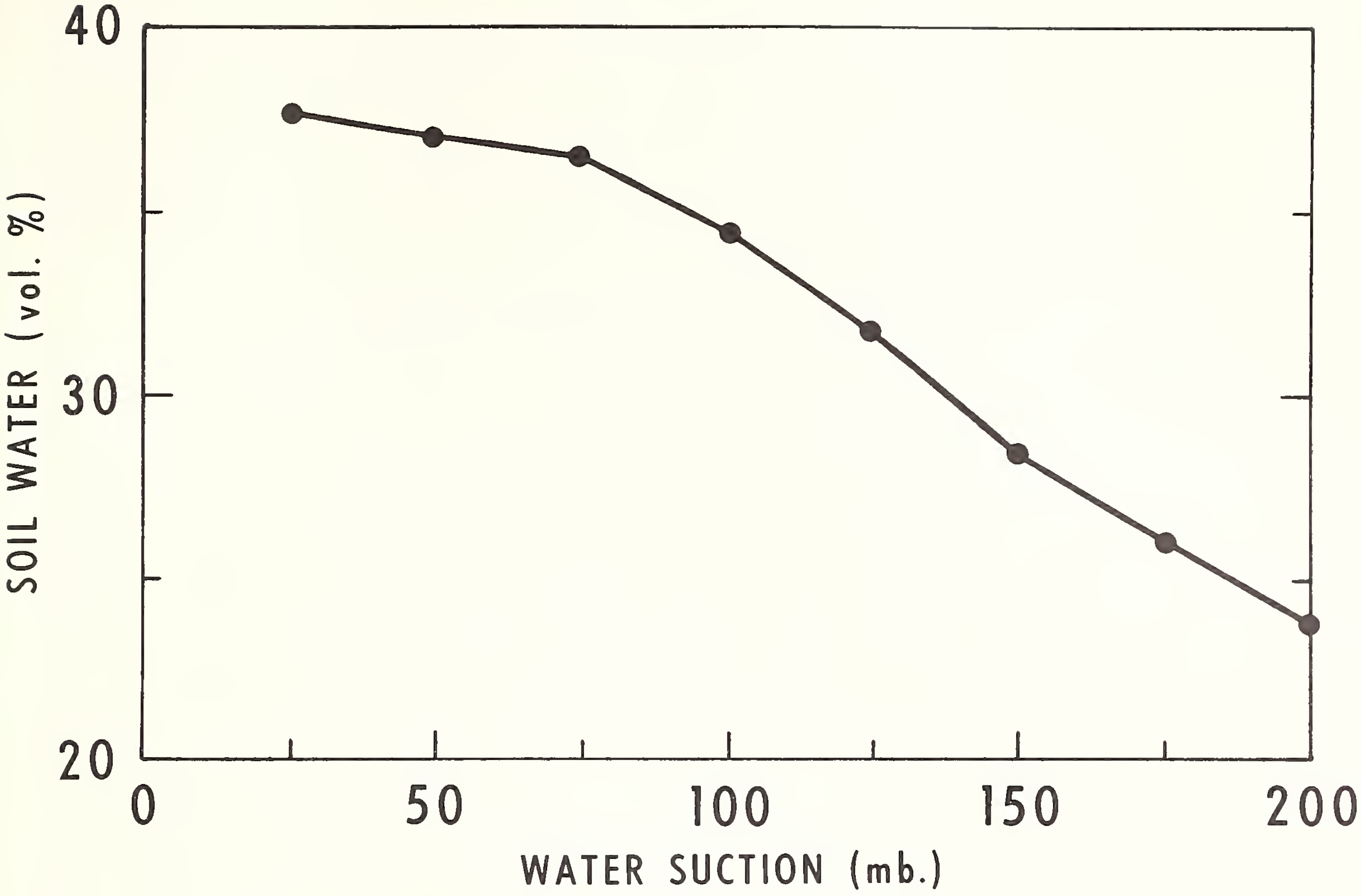

FIGURE 12.—Desorption curve for soil used in constructing model profiles.

interface within a few days after irrigation. Thus the suction distribution in the soil above a coarse layer may be estimated from the unsaturated conductivity curve of the coarse-layer material. From the desorption curve and the estimated suction distributions, an estimate of water-holding capacity can be made.

If one arbitrarily assumes that a drainage rate of about 0.1 to 0.01 cm. per day is negligible, the suction at which such drainage rate (assuming a hydraulic gradient of 1) would take place is about 50 mb. for the sand and about 2 mb. for the gravel (fig. 13). Because of the steepness of the curves, it makes little difference whether one selects 0.1 or 0.01 cm. per day as negligible. The resulting suctions are nearly the same. Thus a soil underlain by sand should drain to a suction of about 50 mb. at the interface and to about 2 mb. if underlain by gravel, and the suction within the soil will increase by about 1 mb. per centimeter increase in height above the layer.

Table 2 shows the actual suctions observed at the soil-layer interface as compared with those estimated from the unsaturated conductivity curve, as discussed previously.

TABLE 2.—*Comparison of observed and estimated soil water suctions at soil-layer interface of stratified profiles*

Profile	Observed suction at indicated days after irrigation				Estimated suction [1]
	3	9	28	62	
	Mb.	*Mb.*	*Mb.*	*Mb.*	*Mb.*
Sand at 61 cm	33	43	45	61	50
Sand at 122 cm	15	23	32	36	50
Gravel at 122 cm	13	13	17	27	2

[1] Suction estimated at interface is that suction in sand or gravel corresponding to an unsaturated conductivity between 0.1 and 0.01 cm. per day.

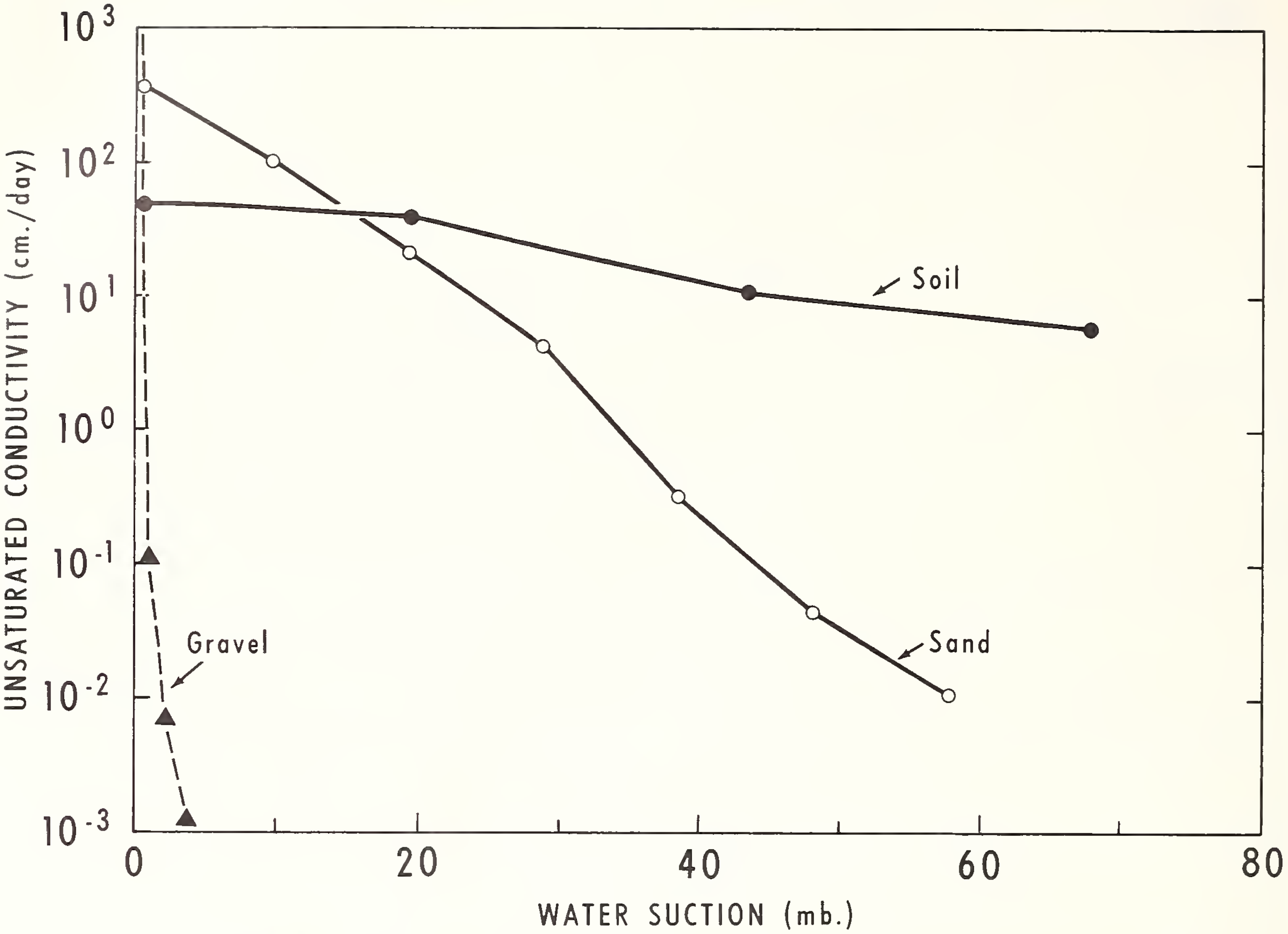

Figure 13.—Unsaturated conductivities of soil, sand, and gravel used in constructing model profiles.

The water suction in the soil overlying the sand was greater in the profile with sand at 61 cm. than in the one with sand at 122 cm. If the unsaturated conductivity of the sand becomes negligible at some suction, the suction in the soil just above the sand should closely approximate this value, regardless of the depth to the sand. However, because of the greater depth of wetted soil, more water had to drain through the layer under conditions of low conductivity when the soil was underlain by sand at 122 cm. as compared with 61 cm. Thus it would take longer to drain to the estimated limiting suction in the deeper soil. There may be differences in the packing of the sand between the two profiles, but such differences should be minor. The soil above the gravel drained to a greater suction than was predicted from the unsaturated conductivity curve. Probably in constructing the profile and during subsequent irrigations, some soil filtered down into the gravel layer and thus increased the suction at which the conductivity became small. However, the suctions shown are low compared with the suction ranges usually associated with nonlayered soils.

In table 3, data are shown comparing the observed water contents at various soil depths with those estimated from the unsaturated conductivity and desorption curves. The estimated suction values are obtained from the estimated limiting suctions in the sand or gravel layer and are corrected for distance above the soil-layer interface by 0.98 mb.-per-centimeter increase in height. The water contents corresponding to these suctions are read from the desorption curve.

In most instances, values similar to the estimates were observed within a few days after irrigation. There are several possible sources of error in this procedure for estimating water retention. There would be some hysteresis effects because the profile soils would have been less nearly saturated before they started to drain than were the laboratory samples. The laboratory samples were wet under atmospheric pressure rather than under vacuum prior to being desorbed to reduce hysteresis effects.

The use of disturbed soil samples to characterize desorption of undisturbed soil will introduce some error. At low suctions small changes in bulk density and pore characteristics may have pronounced effects on the desorption characteristics of the soil.

It is difficult to obtain an accurate sample of a coarse layer to use for unsaturated conductivity determinations. Here also differences in packing will give differences in unsaturated conductivity values.

TABLE 3.—*Comparison of observed and estimated soil water contents and estimated suction at various depths in soil underlain by sand or gravel*

Soil depth and profile	Observed water content at indicated days after irrigation				Estimated	
	3	9	28	62	Water content	Suction
	Vol. percent	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Mb.*
30 cm.						
Sand at 61 cm	34. 8	34. 4	35. 1	34. 3	36. 0	80
Sand at 122 cm	33. 5	32. 2	30. 1	30. 4	29. 5	140
Gravel at 122 cm	32. 3	32. 5	32. 5	31. 7	35. 0	92
61 cm.						
Sand at 122 cm	33. 8	32. 5	32. 4	32. 0	33. 2	110
Gravel at 122 cm	36. 3	37. 1	36. 4	36. 3	36. 7	62
91 cm.						
Sand at 122 cm	37. 8	37. 3	36. 4	36. 3	36. 0	80
Gravel at 122 cm	36. 9	37. 3	36. 6	35. 6	37. 5	32

WATER RETENTION IN FIELD PROFILES

Procedures

Field tests of water retention were made on four naturally occurring profiles of soils in the Ephrata, Timmerman, Rupert, and Scooteney series. All profiles contained coarse layers in the upper meter of soil.

The Ephrata soil is a loam underlain at about a 60-cm. depth by clean, coarse sand and gravel. The interface is sharp. The amount of small rocks in the soil increases with depth to the extent that sampling of the 45- to 60-cm. depth was not possible. However, sufficient soil is in this soil-rock mixture, lying above the sharply defined sand and gravel layer, to make its water-holding capacity important.

The Timmerman soil is a coarse sandy loam underlain at about the 75-cm. depth by clean, coarse sand. The interface between the soil and the underlying sand is indistinct and extends over several centimeters.

The Rupert soil is a coarse sandy loam at the surface. It increases in coarseness with depth until at 45 to 60 cm. the texture becomes a loamy sand. Black sand occurs at about the 75-cm. depth. The interface between the sand and the overlying soil extends over several centimeters.

The Scooteney soil consists of 60 to 100 cm. of silt loam over 15 to 25 cm. of a soil and cobble rock mixture. This material grades into "dirty" sand and gravel, with the amount of soil in the coarse layer decreasing with depth.

Plots of these soils about 3.5 m. square were isolated from the surrounding soil with polyethylene film to prevent lateral flow (*6*). A trench was dug around each plot, lined with the film, and then backfilled. While trenching around each plot, samples of the coarse underlayer were collected for laboratory measurement of unsaturated conductivities. The plots were leveled, thoroughly irrigated by flooding, and then covered with black polyethylene film. Water measurements were made gravimetrically, and suctions were observed with tensiometers for about 2 weeks after irrigation. After field tests were completed, disturbed soil samples from above the coarse layer were taken in depth increments of 15 cm. to be used for laboratory measurement of texture, desorption characteristics, and unsaturated conductivity.

Results and Discussion

From the unsaturated conductivity curves of the coarse-layer material and the desorption curves for the soil, estimates of water-holding characteristics were made and compared with the observed values. To further emphasize that profile characteristics must be considered in estimating water retention in layered soils, estimated available water based on observed field data and on the ⅓-bar percentage for the four soils is given in table 4.

For all these soils, the ⅓-bar percentage is a poor basis for estimating the water-retention properties of the soil. Any other method of estimating water retention that is based on soil texture only, without regard for the profile, will be unsatisfactory. The entire profile must be considered.

The unsaturated conductivity curve for the coarse-layer material of the Ephrata soil is given in figure 14. At 20-mb. suction, the unsaturated conductivity is about 0.02 cm. per day. The soil over this layer at the interface should not drain

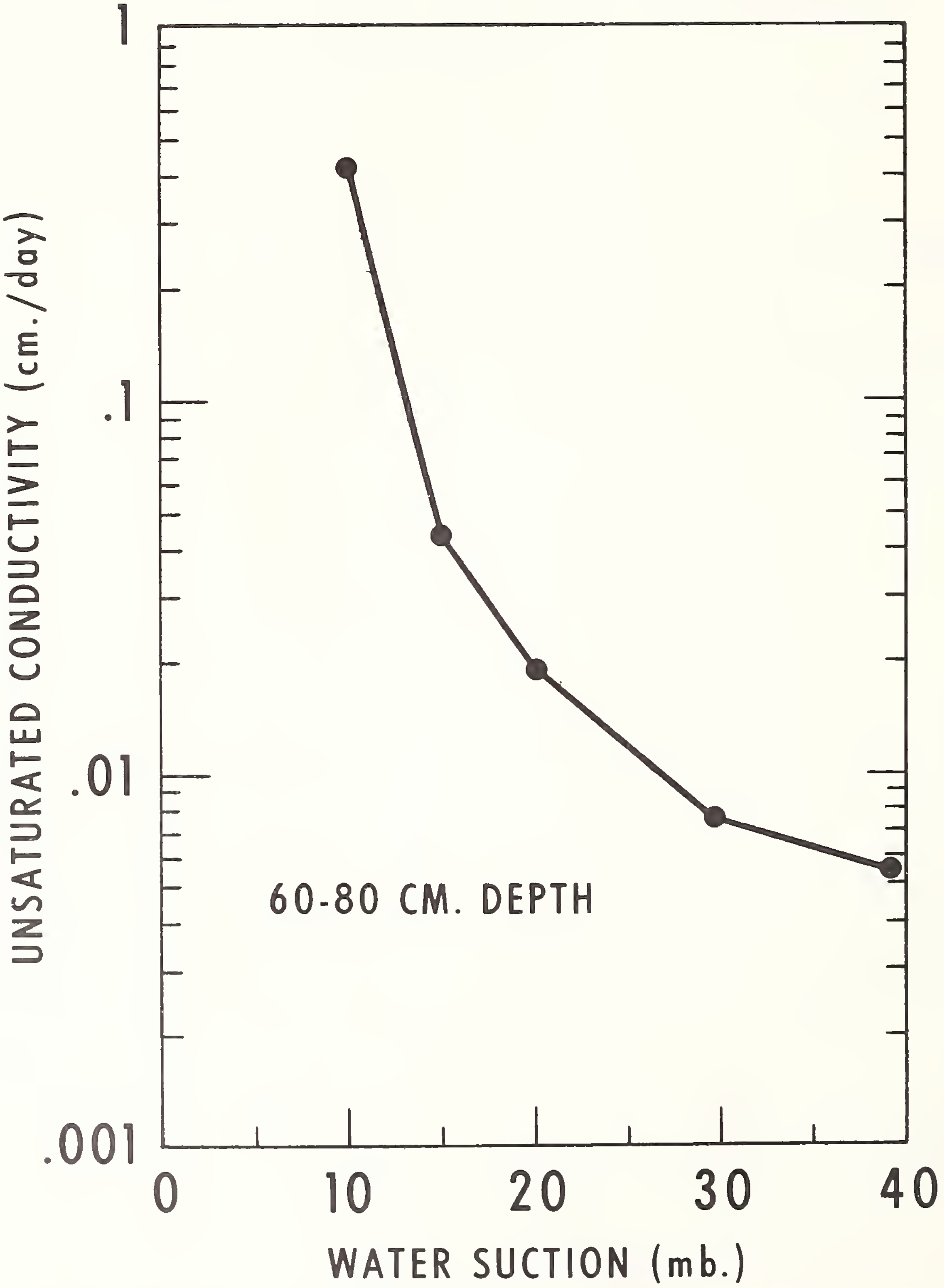

Figure 14.—Unsaturated conductivity curve for coarse layer (60- to 80-cm. depth) of Ephrata soil.

TABLE 4.—*Estimated available water held in various soils several days after irrigation based on observed field value and ⅓-bar percentage*

Soil	Soil depth	Estimated available water based on—		Ratio
		Observed field value minus 15-bar percentage	⅓-bar percentage minus 15-bar percentage	
	Cm.	*Cm.*	*Cm.*	
Ephrata	0–60	14. 6	6. 4	2. 28
Timmerman	0–75	15. 3	6. 6	2. 32
Rupert	0–75	9. 2	4. 5	2. 04
Scooteney	0–90	26. 6	21. 0	1. 27

to suctions much greater than about 20 mb. Estimated suction distributions in Ephrata soil, based on this assumption, are compared with observed values in table 5.

Desorption curves for the 0- to 15-cm. and 15- to 30-cm. depths of Ephrata soil are given in figure 15. From these curves the water content was estimated as indicated by the arrows. The observed and estimated values are compared in table 6.

The estimated amount of water in the 0- to 15-cm. depth of the Ephrata soil agreed with the observed values, but the estimate for the 15- to 30-cm. depth was lower than that observed in the field. The rocks in the soil caused considerable variation in the field water content. However, the estimated value is considered satisfactory. When

TABLE 5.—*Observed and estimated suction distributions in Ephrata soil at various times after irrigation*

Soil depth (cm.)	Observed suction [1] at indicated days after irrigation					Estimated suction
	1	4	6	8	12	
	Mb.	*Mb.*	*Mb.*	*Mb.*	*Mb.*	*Mb.*
15	59	68	69	74	75	65
30	47	55	58	61	65	50
60						20

[1] Data not given for 60-cm. soil depth because tensiometers were not installed on account of rock.

TABLE 6.—*Estimated water content and suction distributions in Ephrata, Timmerman, and Rupert soils as compared with observed water content at various times after irrigation*

Soil depth (cm.)	Observed water content at indicated days after irrigation							Estimated	
	1	4	6	8	12	19	22	Water content	Suction at midpoint
	Vol. percent	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Mb.*
EPHRATA									
0–15	36. 5	32. 1	31. 3	33. 7	35. 0			35. 7	72
15–30	37. 4	36. 8	36. 2	36. 5	36. 5			[1] 32. 8	57
TIMMERMAN									
0–15	32. 4	26. 6		23. 7		23. 3	21. 9	23. 2	152
15–30	28. 9	27. 9		25. 1		23. 2	23. 6	27. 2	137
30–45	31. 1	29. 9		29. 6		27. 9	27. 2	32. 8	122
45–60	30. 6	29. 7		27. 8		25. 4	25. 8	29. 6	107
60–75	27. 2	27. 2		23. 7		22. 2	19. 8	24. 2	92
RUPERT									
0–15	20. 6	18. 0	17. 1	18. 5	18. 9	17. 5		19. 1	159
15–30	22. 4	19. 8	18. 8	19. 7	18. 8	19. 3		21. 0	144
30–45	23. 1	20. 8	18. 9	19. 3	19. 3	18. 8		20. 7	128
45–60	25. 7	21. 1	22. 2	20. 8	20. 4	18. 8		20. 4	113
60–75	19. 8	17. 3	16. 0	14. 1	14. 1	13. 7		13. 9	98

[1] Decrease in water content with depth is associated with increase in rock content with depth.

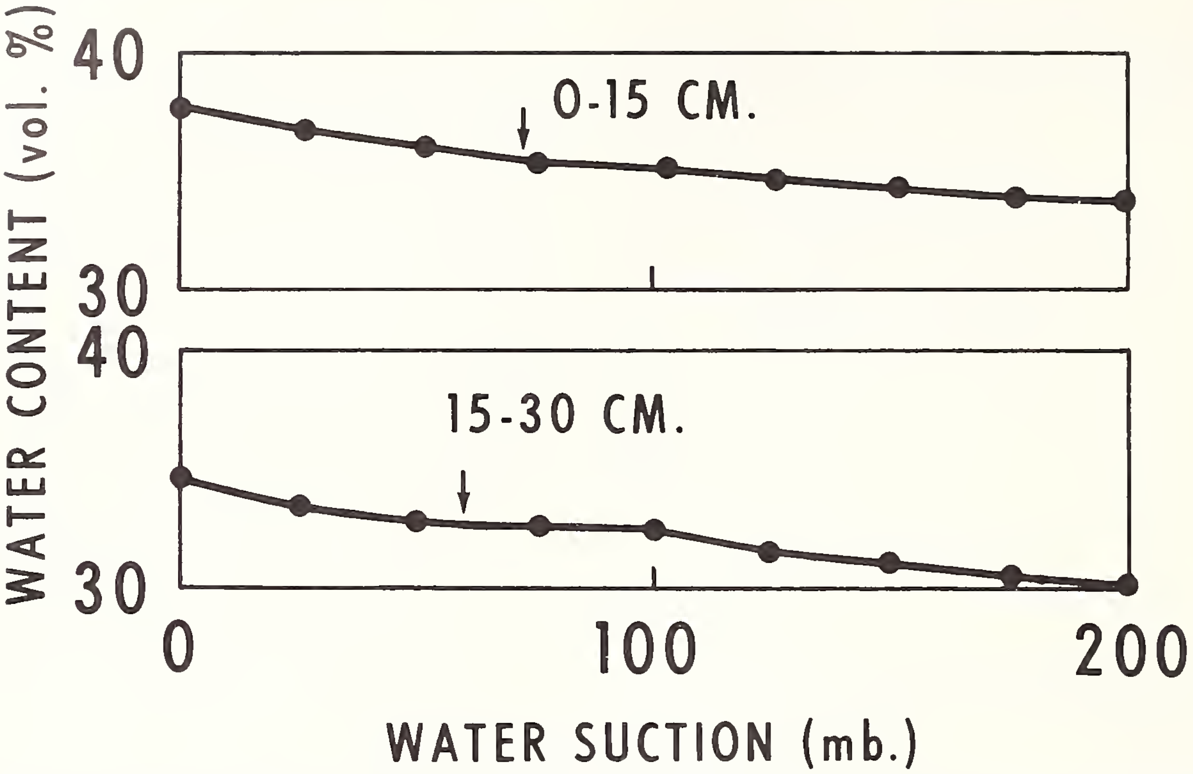

FIGURE 15.—Desorption curves for Ephrata soil. Arrows indicate water content corresponding to estimated suction at center of depth increment.

sampling this soil, it was common to encounter rocks with the sampling tube. Several locations often had to be tried before a 30-cm. depth was reached. The rock content of the soil as a whole was greater than that of the sample and consequently its water content was lower.

Using the same procedure, estimates of water content and suction distributions for the Timmerman and Rupert soils were made and compared with observed field values (table 6).

The estimated water content usually was observed in the field within a few days after irrigation. These estimates are considered sufficiently accurate for field use in predicting the water retained by these soils after irrigation.

However, estimates of the suction distribution in these two soils were less satisfactory than those made from the Ephrata soil in that they were too high. Apparently in the field the coarse layers composed largely of sands, as in the Timmerman and Rupert soils, conduct less water than the laboratory data indicated. Some of this error is probably due to hysteresis, because in the laboratory the materials were saturated and then drained to a given suction, whereas in the field the coarse layers would have become wet and drained under a finite suction. Thus at a given water suction the field material would contain less water and have a lower unsaturated conductivity than would a laboratory sample. As a result, a negligible drainage rate would be observed in the field at a lower suction than that predicted from the laboratory data.

For the Scooteney soil, in which about 25 percent of the material in the coarse layer was less than 0.25 mm. in diameter, laboratory estimates of water and suction distribution were poor. Estimated suctions were much too high. Part of the error in these estimates could be due to hysteresis. In addition, the soil-size material in the coarse layer of the Scooteney soil often occurred in small pockets. In the sample used in the unsaturated conductivity tests, all the coarse-layer material was mixed together. The fine material apparently increased the effective unsaturated conductivity of the coarse material more when it was mixed uniformly throughout the coarse material than when it occurred in pockets as observed in the field.

The data from these four field soils indicate that satisfactory estimates of water-retention properties of layered soils can be made from desorption curves of the soil and unsaturated conductivities of coarse materials when the interface between the soil and layer is sharp and the underlying material coarse. Less satisfactory but usable estimates are possible when the underlying layer is coarse to fine sand and the interface is not distinct. If the underlayer contains appreciable soil-size material, estimates are not reliable.

Determination of an unsaturated conductivity curve is tedious. Therefore, it is desirable to have some way of estimating the limiting suction associated with a coarse layer without requiring such a curve. Unsaturated conductivity curves were prepared for various sand fractions (fig. 16).

These data indicate that if the underlying coarse material in a layered soil is greater than 0.25-mm. diameter, the suction at the soil-layer interface would not be expected to be larger than about 40

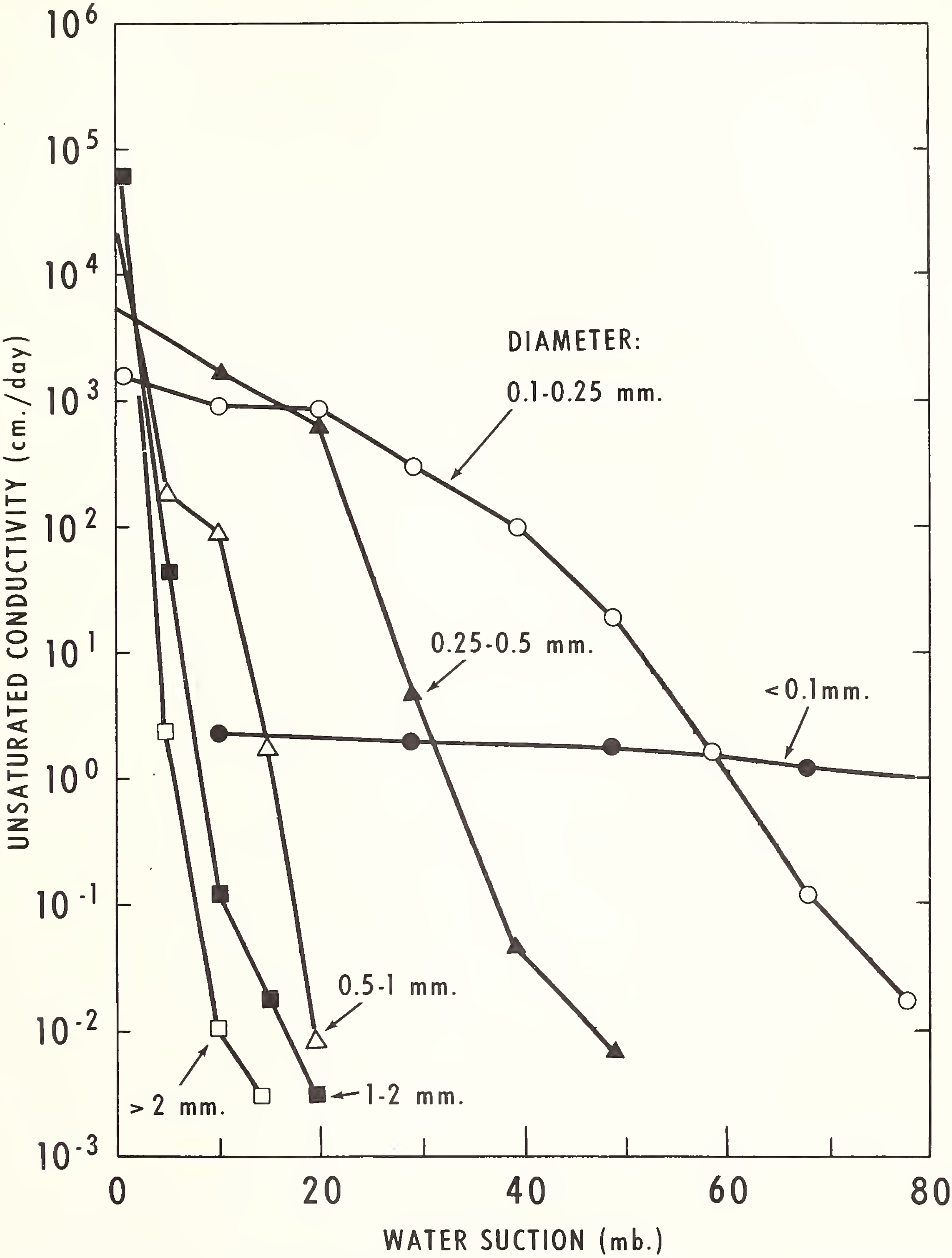

FIGURE 16.—Unsaturated conductivity curves for various sand fractions sieved from model profile sand. Each plotted point is average of three determinations.

mb. within a few days after a thorough irrigation. If appreciable soil-size material (<0.1 mm.) is present, the expected suctions will increase. Thus it should be possible to arrive at a reasonable suction value for many soils by considering the amount of coarse-layer material that is <0.1 and from 0.1 to 0.25 mm. in diameter.

After each unsaturated conductivity test for coarse materials from the model and field profiles, the material in each flow cell was dried and the particle-size distribution determined by dry sieving. The unsaturated conductivities were then qualitatively related to the amount of soil-size material in the coarse layer, as indicated in table 7.

If the coarse material contains less than about 1 percent of <0.1-mm. material, soil over such material should not drain to suctions greater than about 50 mb. at the interface. The expected suction increases with the amount of <0.1-mm. material to about 70 mb. for 4 percent.

When the amount of <0.1–mm. material is about 7 percent, the expected suction will exceed 70 mb. (about 90 mb. in the Rupert soil). Thus, based on the amount of <0.1–mm. material in the coarse layer, one may roughly estimate the suction at the interface between soil and layer. The estimate will be less satisfactory as the amount of fine material in the layer increases.

TABLE 7.—*Qualitative relationship between unsaturated conductivities and amount of <0.1- and 0.1- to 0.25-mm. fractions in coarse material*

Source of coarse material	Unsaturated conductivity at indicated suction (mb.)				Amount of indicated fraction in coarse material	
	10	30	50	70	<0.1 mm.	0.1–0.25 mm.
	Cm. per day	*Cm. per day*	*Cm. per day*	*Cm. per day*	*Percent*	*Percent*
Model profiles	96.7	4.0	0.043	0.011	1.0	5.0
Ephrata	.59	.010	--------	--------	1.0	.9
Timmerman	4.58	.145	.058	.033	3.9	2.6
Rupert	24.1	5.43	.840	.138	6.8	13.2
Scooteney	7.0	2.64	1.57	[1] 1.29	18.0	6.6

[1] 60-mb. suction.

NUMERICAL TECHNIQUES

A digital computer was used to evaluate the effect of soil depth over a layer and the coarseness of the underlying layer on water retention by soil. The computer program developed by Hanks and Bowers (*3*) was used. Laboratory desorption and unsaturated conductivity data for the model profile soil and sand were utilized in preparing the tables required by the computer program (tables of suction and diffusivity at various water contents).

Evaluations made with the computer include—

(1) Comparison of observed and computed data for model profiles for 61 cm. (2 ft.) and 122 cm. (4 ft.) of soil overlying sand.

(2) Computed data for 183 cm. (6 ft.) of soil over sand.

(3) Computed data showing effect of varying coarseness of underlying layer on water retained by overlying soil. The similar media concept of Miller and Miller (*9*) was utilized to obtain desorption and unsaturated conductivity data for the various coarse layers.

Comparison of Observed and Computed Data

An example of the data obtained with the computer is shown in table 8 for 61 cm. of soil overlying the sand.

A comparison of observed and computed water-retention data is given in table 9 for 61 and 122 cm. of soil underlain by sand.

The computed data in table 9 agree satisfactorily with the observed data, except that the observed water content in 61 cm. of soil is lower than the computed values by about 1 percent by volume. Inasmuch as the suction values agree rather well, the discrepancy probably is due to the laboratory desorption curve being slightly different from the curve for the soil in this profile. For 122 cm. of soil, observed and computed data for both water content and suction agree satisfactorily.

TABLE 8.—*Soil water content and suction distributions in profile with 61 cm. of soil overlying sand as affected by time after irrigation (computed data). Bottom of sand at 99-cm. depth was maintained at 9 percent water by volume and 31.2 mb. suction by computer program*

Soil depth (cm.) [1]	Water content at indicated days after irrigation			Water suction at indicated days after irrigation		
	3	7	14	3	7	14
	Vol. percent	*Vol. percent*	*Vol. percent*	*Mb.*	*Mb.*	*Mb.*
2.5	33. 8	33. 4	33. 4	105	109	109
12.7	34. 7	34. 4	34. 4	95	98	98
22.9	35. 5	35. 3	35. 3	86	88	88
33.0	36. 1	36. 1	36. 1	76	78	78
43.2	36. 5	36. 4	36. 4	66	68	68
53.3	36. 8	36. 7	36. 7	55	58	58
63.5	6. 5	6. 0	6. 0	47	51	51
73.7	6. 7	5. 9	5. 9	46	54	54
83.8	7. 0	6. 7	6. 7	44	46	46
94.0	8. 3	8. 2	8. 2	36	36	36

[1] Increments of 5.1 cm. (2 in.). At 61 cm., soil-sand interface.

TABLE 9.—*Comparison of observed and computed water content and suction distributions in 61 and 122 cm. of soil underlain by sand at various times after irrigation*

61 CM. OF SOIL

Soil depth (cm.)	Observed water content at indicated days after irrigation			Computed water content at indicated days after irrigation		
	3	7	14	3	7	14
	Vol. percent	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*
23	34. 4	33. 9	33. 6	35. 5	35. 3	35. 3
30	34. 8	34. 4	34. 5	36. 0	35. 9	35. 9
38	35. 1	35. 1	34. 9	36. 3	36. 2	36. 2
	Observed water suction			Computed water suction		
	Mb.	*Mb.*	*Mb.*	*Mb.*	*Mb.*	*Mb.*
15	81	89	88	91	96	96
30	62	75	73	76	81	81
56	40	49	47	51	55	56

122 CM. OF SOIL

Soil depth (cm.)	Observed water content at indicated days after irrigation			Computed water content at indicated days after irrigation		
	3	7	14	3	7	14
	Vol. percent	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*	*Vol. percent*
30	33. 5	32. 4	31. 0	33. 7	32. 4	31. 4
61	33. 8	33. 3	32. 6	34. 8	34. 2	33. 8
91	37. 8	37. 3	37. 4	36. 4	36. 2	36. 1
99	36. 7	37. 5	36. 6	36. 6	36. 5	36. 3
	Observed water suction			Computed water suction		
	Mb.	*Mb.*	*Mb.*	*Mb.*	*Mb.*	*Mb.*
15	117	128	132	111	126	135
30	102	113	117	105	118	126
56	79	88	90	96	104	109
91	50	56	58	68	74	78
114	23	31	35	46	51	55

Effect of Soil Depth Over Coarse Layer on Water Retention

The close agreement in table 9 was taken as evidence that satisfactory water-retention data could be computed. Accordingly, soil water and suction distributions with time were computed for a profile with 183 cm. (6 ft.) of soil underlain by sand. Thus comparisons are available among profiles with 61, 122, or 183 cm. of soil over the sand.

The 15-bar percentage of the soil is about 8.4 percent by volume. The computed data were converted to available water and compared with that in uniform soil in table 10. To remove the error associated with the desorption curve, the water content in the uniform soil was obtained by taking the observed suction distribution and applying this distribution to the laboratory desorption curve. On this basis the available water in the upper 61 cm. of soil 1 week after irrigation was 11.2 cm. or 5.6 cm. per 30 cm. This value was used for the uniform soil for all comparisons, which are based on data 1 week after irrigation. Any effect of depth of wetting on water content was disregarded.

These data illustrate that in terms of available water per unit depth of soil, the greatest increase is in the soil adjacent to the coarse layer. As the depth of soil above the layer increases, the water suction also increases, and at great enough soil depths the suction and water in the surface soil approach those for a uniform soil.

Effect of Particle Size in Coarse Layer on Water Retention

In addition to the results computed for soil overlying sand (table 10), the effect of varying the coarseness of the underlying layer on the water retention by the soil was evaluated by utilizing the similar media concept. With this procedure, an arbitrary length (diameter) is assigned to a reference coarse material, and other coarse materials are assigned lengths that are multiples of this reference length. From the desorption, unsaturated conductivity, and diffusivity curves for a reference material, curves can be calculated for other materials.

The sand from the model profiles (same sand as discussed previously in this report) was assigned a length of $L=2$ mm. Desorption and diffusivity curves were calculated for materials with $L=0.5$, 1, and 10 mm. Although the reference sand was not uniformly 2 mm. in length, this is immaterial. The similar media concept considers each particle in the reference medium to have a diameter some multiple of a corresponding diameter in a second medium. For example, if $L=1$ mm., for each particle in the reference sand ($L=2$ mm.), there is a similarly shaped particle in the second sand, but its length is one-half that of the reference particle. For a material with $L=10$ mm., each particle will have a length dimension five times that of a corresponding particle in the reference material $\left(\frac{L=1}{L=2}=\frac{1}{2};\ \frac{10}{2}=5\right)$.

TABLE 10.—*Effect of soil depth overlying sand layer on available water retained by soil 1 week after irrigation*

Soil depth (cm.)	Available water in uniform soil	Available water in indicated amount of soil over sand		
		61 cm.	122 cm.	183 cm.
	Cm.	*Cm.*	*Cm.*	*Cm.*
0–30	5.6	8.1	7.1	6.8
30–61	5.6	8.6	7.6	7.4
61–91	5.6		8.1	7.6
91–122	5.6		8.6	7.9
122–152	5.6			8.4
152–183	5.6			8.6
Total	33.6	16.7	31.4	46.7
Layered soil[1] / Uniform soil		1.50	1.41	1.39

[1] Based on equal soil depths.

At a given water content the reduced suction, $S.$, is given by

$$S.=\frac{LS}{\sigma} \qquad (1)$$

Where L is the characteristic length of the medium, S is suction, and σ is surface tension of the liquid. The reduced diffusivity, $D.$, is given by

$$D.=\frac{\mu}{L\sigma}D\frac{(LS)}{(\sigma)} \qquad (2)$$

Where μ is fluid viscosity, D is diffusivity, and L, σ, and S have the same meanings as in equation (1).

At a given water content the reduced suction and diffusivity will be the same for all similar media.

If only the characteristic length L is varied, the fluid viscosity and surface tension do not change. Thus using subscripts 1 and 2 to refer to a reference medium, 1, and a second medium, 2, suctions in two similar media are related by

$$L_1S_1=L_2S_2 \qquad (3)$$

$$S_2=\frac{L_1}{L_2}S_1$$

The diffusivities are related by

$$\frac{D_1}{L_1}=\frac{D_2}{L_2} \text{ or } D_2=\frac{L_2}{L_1}D_1 \tag{4}$$

If the suction and diffusivity as functions of water content are known for a reference medium, the suctions and diffusivities can be calculated for a similar medium that differs only in a characteristic length.

With the model profile sand as a reference ($L=2$ mm.), desorption and diffusivity data were calculated for similar media with $L=0.5$, 1, and 10 mm. Some of the data calculated for media with $L=0.5$ are given in table 11.

The desorption and diffusivity data for the model profile soil (same soil referred to previously in this report) and the calculated coarse-material data were used to compute the effect of varying coarse layers on water retention by the soil. A soil depth of 61 cm. was used in all tests.

The computed water content and suction distributions are shown in figures 17 and 18. In the soil underlain by materials with $L=2$ and 10 mm., hydraulic gradients approached zero within 1 or 2 days after irrigation, and water content and suction did not change significantly thereafter. In soil underlain by material with $L=0.5$ mm., the hydraulic gradients did not approach zero, and water continued to drain from the soil throughout the 14-day computation period. At 14 days the average hydraulic gradient from the 2.5-cm. depth to the 58-cm. depth was -0.6 (upward as positive) for $L=0.5$, -0.12 for $L=1$, -0.005 for $L=2$, and 0 for $L=10$ mm.

If the computed data are converted to available water in the soil above the coarse layers 1 week after irrigation, the data in table 12 are obtained.

These computed values substantiate data previously shown. The increase in available water in a layered soil compared with a uniform soil, in terms of depth of water per unit depth of soil, is greater as the underlying material becomes coarser, and the increase is greatest adjacent to the soil-layer interface. The water increases are explained by the suction distributions in the soil. These, in turn, are determined by the unsaturated conductivity of the coarse layer and the height of soil above the interface.

TABLE 11.—*Desorption and diffusivity data calculated for media with $L_2=0.5$ mm., using sand with $L_1=2$ mm. as a reference (see equations 3 and 4)*

Water content (vol. percent)	$L_1=2$ mm. (reference)		$L_2=0.5$ mm.	
	Suction	Diffusivity	Suction	Diffusivity
	Mb.	*Cm.² per min.*	*Mb.*	*Cm.² per min.*
10	28.2	0.854	112.8	0.214
15	19.5	2.00	78.0	.500
20	14.8	2.82	59.2	.705
25	11.2	2.90	44.8	.725

TABLE 12.—*Available water held in 61-cm. deep soil 1 week after irrigation as affected by varying coarseness of underlying layer (computed data)*

Soil depth (cm.)	Available water in uniform soil	Available water when coarseness of underlying layer (L) is—			
		0.5 mm.	1 mm.	2 mm.	10 mm.
	Cm.	*Cm.*	*Cm.*	*Cm.*	*Cm.*
0–30	5.6	7.1	7.4	8.1	8.6
30–61	5.6	7.4	8.1	8.6	8.9
Total	11.2	14.5	15.5	16.7	17.5
$\frac{\text{Layered soil}}{\text{Uniform soil}}$		1.30	1.39	1.50	1.57

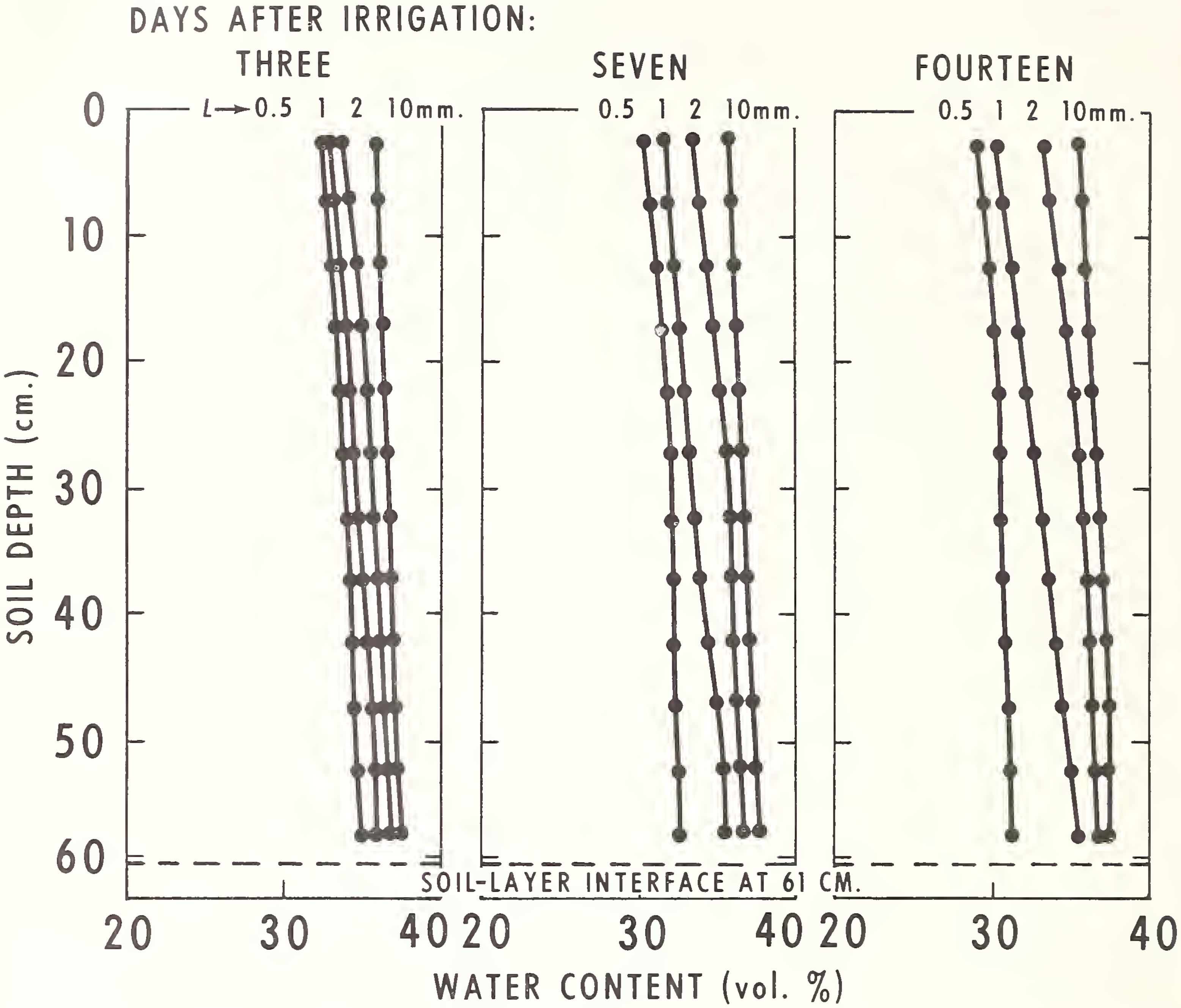

FIGURE 17.—Water contents as affected by size of underlying material (*L*) and time after irrigation (computed data).

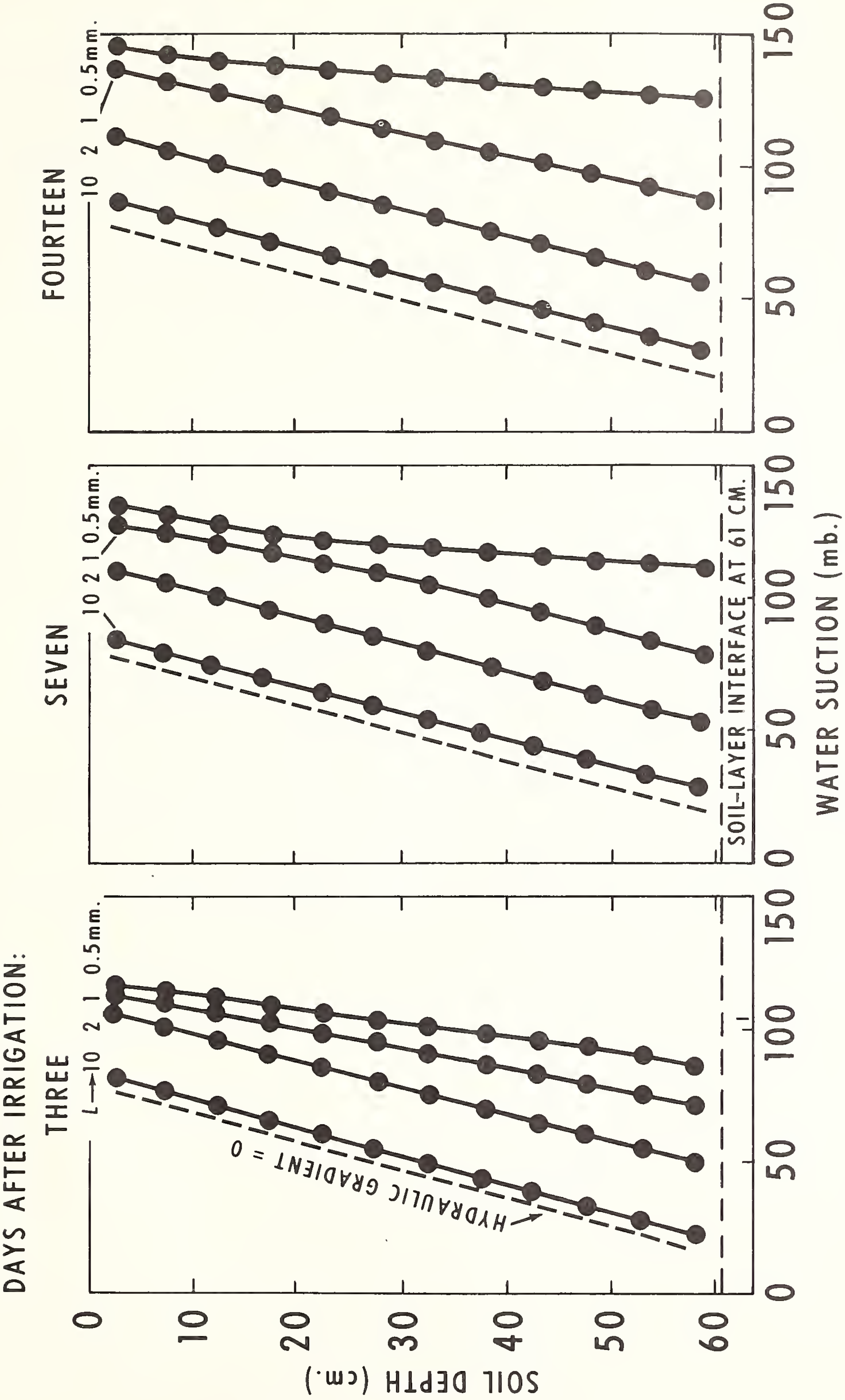

FIGURE 18.—Water suctions as affected by size of underlying material (*L*) and time after irrigation (computed data).

SUMMARY

The water retained by a soil is affected by the characteristics of the entire wetted part of the profile. The effect of coarse layers in the profile on water-holding characteristics must be understood for proper management of irrigation. Recent research showing the effect of coarse layers on water retention is presented. Also ways of estimating water-retention properties of layered soils are discussed.

In terms of the conventional available water, a layered soil will hold 50 to 60 percent more available water than will a similar depth of uniform soil. The differences in water retention are determined by the unsaturated conductivity of the coarse layer and by the desorption characteristics of the soil above the layer.

Satisfactory laboratory estimates of water retention can be made for layered soils when the underlying layer is clean and coarse. When the underlying layer contains appreciable soil-sized material, estimates are not reliable.

The amount of water held by a layered soil increases as the underlying particles become coarser and is greatest adjacent to the soil-layer interface. It decreases with elevation above the layer.

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